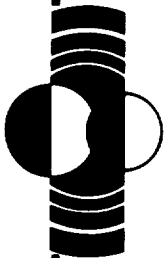


# Lunar and Planetary Science XXIII



*Abstracts of papers submitted to the  
Twenty-Third Lunar and Planetary  
Science Conference*

P-61

**PRESS ABSTRACTS**

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## PREFACE

The Program Committee for the Twenty-Third Lunar and Planetary Science Conference has chosen these contributions as having the greatest potential interest for the general public. The papers in this collection have been written for general presentation, avoiding jargon and unnecessarily complex terms. More technical abstracts will be found in *Lunar and Planetary Science XXIII*.

For assistance during the conference, call the NASA Johnson Space Center News Center at 713-483-5111. Telephone numbers of the first author of each contribution will be found on page iii. Feel free to call for more information.

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**TEM STUDIES OF A CIRCUMSTELLAR ROCK;** Thomas J.

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In this paper we report the discovery of crystals of titanium carbide in a grain of silicon carbide which formed as a circumstellar dust particle in the atmosphere of a carbon-rich star. Just as in the case of terrestrial rocks, whose assemblage of minerals gives us clues to the composition and physical conditions of the environment in which they formed, the titanium carbide crystals and their textural relationship to the silicon carbide give us important clues to the nature of the stellar atmosphere in which they formed.

For more than a half century astronomers have been aware of the presence of interstellar dust from its obscuring effects on the light from stars. From various kinds of studies they have also been able to divine some notion of its composition and particle sizes. Large clouds of interstellar dust and gas can gravitationally collapse to form new stars. Nuclear reactions within these new stars alter the composition of the original gas and dust constituents, and stellar winds spew this altered material back into the interstellar medium. Thus, the chemical composition of the galaxy evolves with time.

Cosmochemists have long known that the sun and the planets owe their particular compositions to a mixture of interstellar gas and dust, but it was thought until fairly recently that all vestiges of the original constituents had been erased by complete homogenization of the dust component very early in the formation of our solar system. The evidence for this idea was based on the observation that the isotope composition of the more abundant elements was the same regardless of whether one was making measurements on a terrestrial rock, a moon rock or a meteorite. Any differences that were observed could usually be explained as the result of well-understood nuclear and chemical processes that occur within the solar system. However, some poorly understood variations in isotope composition occurred in the noble gases, which are generally present in very low abundances in solid materials. It was in an effort to isolate the mineral carriers of these noble gases that Edward Anders and his colleagues at the University of Chicago began nearly two decades ago to chemically treat primitive meteorites in order to dissolve away unwanted minerals and concentrate the carriers of unusual neon and xenon. These chemical processing procedures eventually led to the discovery of meteorite grains which could unambiguously be pronounced as stardust -- circumstellar grains which condensed in the atmospheres of diverse types of stars, were expelled from these atmospheres and existed for a time as interstellar grains, and which finally were incorporated into the interstellar cloud from which our solar system formed, but nonetheless had survived all of these tumultuous events.

To date, small interstellar grains of diamond, silicon carbide and graphite (sometimes containing titanium carbide) have been found. It is fair to ask how we can be confident that these grains really are stellar condensates, and not simply minerals that formed in our own solar system. Because of advances in microanalytical techniques, it is possible to measure the isotope composition of some abundant elements in individual grains, many of which are so small as to be invisible to the naked eye. We find that the compositions of some are dramatically different from the average solar system composition. For example, in typical solar system material, variations of a few percent in the proportions of the two isotopes carbon-12 and carbon-13 would normally be considered large; but in individual interstellar carbon grains the proportions can be as much as fifty times the solar system average value. This difference is comprehensible if we consider that carbon in the solar system represents an average of carbon from many different stars, while an individual interstellar graphite grain, for example, represents only the carbon from one particular star which need not have carbon isotope abundances similar to this average.

In our current work we have combined isotope studies of individual interstellar silicon carbide grains from the Murchison meteorite with studies of the interiors of these grains with the transmission electron microscope (TEM). These grains are very small (only a few thousandths of a millimeter in size), yet after isotope measurements it is nonetheless possible to pick up a particle with delicate apparatus, imbed it in a special hard resin, and slice it, using a microtome with a diamond blade, into wafers each only a few hundred atoms thick. This is necessary because, even though the particles are very small, they are too thick to be studied in the TEM. Once such slices have been obtained, it is possible to view features of the grain even down to the size of individual layers of atoms.

Previous studies had shown that some interstellar silicon carbide has fairly high concentrations of elements such as aluminum and titanium, and we wondered if there might be distinct minerals containing them within the silicon carbide. TEM examination of slices of one silicon carbide grain revealed that although aluminum is apparently dispersed as atoms throughout the grain, the titanium is indeed present in crystals of titanium carbide. The titanium carbide crystals are very small, only a few hundred to a few thousand atoms wide. Even though the crystals are themselves too small for isotope study, the fact that they are contained within a demonstrably circumstellar silicon carbide grain means that they must also be stellar condensates--part of a micro-rock which formed in the atmosphere of a star before the birth of our own sun.

Chemical equilibrium calculations made in 1978 by Lattimer, Schramm and Grossman at the University of Chicago had predicted that these two minerals, silicon carbide and titanium carbide, would be some of the first to condense in the atmosphere of a carbon-rich star. According to their

calculations, titanium carbide should condense first, followed by silicon carbide, at temperatures of 1300-1500 degrees Celsius. Despite the general agreement with the kinds of minerals that the equilibrium calculations predict should form, in detail things are not this simple. From microscopic studies of the relationships between the atomic planes of the silicon carbide and the titanium carbide, we can show that the titanium carbide cannot have existed as already-formed crystals in a gas around which silicon carbide subsequently condensed. An alternative possibility is that both minerals grew quickly and simultaneously from condensing gas in the rapidly cooling and expanding stellar atmosphere. Other microscopic features of the silicon carbide, such as abundant atomic layer disorder and crystal twinning, similarly suggest rapid grain growth. However, another possibility is that the titanium carbide grew inside of the silicon carbide by diffusion of titanium atoms. Our calculations suggest that this scenario is less likely, given the relatively short times (a year or less) for which stellar condensates can be expected to be exposed to temperatures high enough to make diffusion sufficiently rapid.

No one has yet observed titanium carbide by conventional astronomical measurements of stars or the interstellar medium. This is perhaps not surprising, since this mineral comprises less than one-tenth of one percent of the silicon carbide grain we studied. But it points out that the laboratory study of interstellar grains extracted from primitive meteorites may yield a far richer and more complete picture of how such grains form and how complicated they are than can be gotten from traditional astronomical studies alone. Such laboratory observations pose interesting challenges to theoreticians who model the chemistry of stars and the formation of solid grains in their atmospheres.

## FRACTAL ANALYSIS: A NEW REMOTE SENSING TOOL FOR LAVA FLOWS

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Volcanism is a fundamental planetary process. It shapes a planet's landscape, contributes to its crustal evolution and mantle differentiation, records a planet's thermal history, and releases volatiles to the surface. Much intellectual energy has gone into unraveling volcanic histories by studying the products of volcanism, and many important quantitative parameters have been developed that relate to the rheology and eruption and emplacement mechanics of lavas. Our research centers on developing additional, unique parameters to add to this matrix of properties: the fractal properties of lava flows.

Fractals are objects that look similar at all scales; they are "self-similar" or "scale-invariant". Many natural features are fractals, such as rocky coastlines, talus piles, clouds, river networks and trees, and they can be described by a property called their fractal dimension. The fractal dimension of a curve (such as a lava flow margin) is a measure of how completely a line (one dimension) fills a plane (2 dimension), and thus lies between 1 and 2. A lava flow margin that could be closely approximated by a straight line would have a fractal dimension close to 1, whereas those lava flow outlines that are characterized by many embayments and protrusions would have higher fractal dimensions.

There are several methods of calculating the fractal dimension of a lava flow margin. In this study we used the "structured-walk" or "divider" method. In this method, we measure the length of a given lava flow margin by walking rods of different lengths along the margin. Since smaller rod lengths traverse more smaller-scaled features in the flow margin, the apparent length of the flow outline will increase as the length of the measuring rod decreases. By plotting the apparent length of the flow outline as a function of the length of the measuring rod on a log-log plot, fractal behavior can be determined. A linear trend on a log-log plot indicates the data are fractal. The fractal dimension can then be calculated from the slope of the linear least squares fit line to the data.

We have used this "structured-walk" method to calculate the fractal dimension of many lava flows using a wide range of rod lengths, from 1/8 to 16 meters, in field studies of the Hawaiian islands. We also used this method to calculate fractal dimensions from aerial photographs of lava

flows in the Hawaiian islands, Idaho and the Galapagos Islands, using rod lengths ranging from 20 meters to over 2 kilometers. Finally, we applied this method to orbital images of extraterrestrial lava flows on Venus, Mars and the Moon, using rod lengths up to 60 kilometers. Thus, combining the field, aerial photograph and orbital image data sets, we have studied the fractal properties of lava flows at over five orders of magnitude in scale (rod lengths ranging from 1/8 meter to 60 kilometers).

Thus far, we have made two important discoveries. First, our results indicate that lava flow margins are fractals. In other words, lava flow shape appears to be scale-invariant (at least over the five orders of magnitude in scale that we measured). This observation has important implications for understanding the fluid dynamics of lava flows. The mere fact that flow outlines appear to be fractals suggests that nonlinear forces are operating during flow emplacement because linear equations cannot produce fractals. We are currently investigating the nature of these nonlinear processes in collaboration with S. Baloga of the Jet Propulsion Laboratory (NASA).

Our second major finding is that different types of lava flows appear to have different ranges of fractal dimensions. We measured many examples of basaltic lava flows in Hawaii, Idaho and the Galapagos Islands. The two endmember types of basaltic lava flows are called "a'a" and "pahoehoe". Pahoehoe lavas tend to be smooth-surfaced, and are sometimes characterized by ropy or shelly surface textures. In contrast, a'a flows have rough, clinkery surfaces. Whether an erupting lava is emplaced as a'a or pahoehoe depends on a critical relationship between volumetric flow rate and viscosity. Pahoehoe flows are generally associated with low volumetric flow rates and/or relatively fluid lavas, whereas a'a formation is favored by high flow rates and/or viscous lavas.

The majority of the a'a flows we have measured have significantly lower fractal dimensions than the pahoehoe flows. In fact, a'a and pahoehoe lava flow types each appear to have a distinct, restricted range of fractal dimensions, regardless of geographic location. This corresponds to our observation that the outlines of a'a and pahoehoe flows are qualitatively different: pahoehoe flows tend to have many more protrusions and embayments. These data suggest we can use fractal dimension to remotely distinguish between a'a and pahoehoe flows. Distinguishing a'a and pahoehoe by their fractal dimensions has tremendous potential as a remote sensing tool, for inaccessible areas of the Earth as well as for other planets. This can lead to a better understanding of physical volcanologic processes, as the difference between a'a and pahoehoe lavas are linked to differences in mass eruption rates and magma viscosities. Furthermore, these lava flow types are also usually associated with particular eruptive styles (e.g., fountaining, no fountaining, channel formation, lava tube formation), and may even be indicative of the plumbing system supplying that particular eruption.

We have begun to explore the potential of fractal analysis as a remote sensing tool for other planetary bodies. To date, we have measured extraterrestrial flows from orbital images of Venus,

Mars and the Moon. All are fractal and have fractal dimensions consistent with the range of terrestrial a'a and pahoehoe values. We measured the Venusian flows (three in total) from Magellan radar-backscatter images (not photographs). Two of the flows appear bright and one is dark on these radar backscatter images. Surface roughness is a major contributor to the radar backscatter signal: rougher surfaces tend to produce brighter images. Therefore, one would expect a'a flows, with their rough, clinkery surfaces, to be relatively radar-bright and smooth-surfaced pahoehoe flows to be radar-dark. Interestingly, the Venusian radar-bright flows have fractal dimensions consistent with the range of terrestrial a'a values, whereas the radar-dark flow has a fractal dimension typical of terrestrial pahoehoe flows. These data suggest that both a'a and pahoehoe flow types exist on Venus, and they can be distinguished remotely by fractal dimension.

On Mars, we measured two flows from Viking Orbiter photographic images. One of these yields a fractal dimension consistent with the range of terrestrial a'a values; the second has a fractal dimension value well within the terrestrial pahoehoe range. This suggests that both a'a and pahoehoe flows exist on Mars. On the Moon, we have only measured one flow to date, from Apollo 15 photographic images. We calculated a fractal dimension which (based on terrestrial analogy) suggests pahoehoe.

Clearly, many more lava flows still need to be measured, on Earth as well as on the other planets to further explore the fractal nature of lava flows. But these preliminary results are exciting and encouraging. These data indicate that lava flow margins are fractals, providing insight into the dynamical processes operating during flow emplacement. Furthermore, these data strongly indicate that different flow types have different fractal dimensions. Distinguishing a'a and pahoehoe by their fractal dimensions has tremendous potential as a remote sensing tool, as it can shed light on physical volcanological processes such as mass eruption rates and viscosity relations.



## Environment Modelling in Near Earth Space: Preliminary LDEF Results

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### INTRODUCTION

Near-Earth space is a dynamic environment. Currently, the volume of space debris is increasing at a rate of 5% per year, but is expected to reach a 20% growth rate within the next two decades. With the Space Exploration Initiative (SEI) on the forefront and upcoming space travel becoming more of a reality, much more man-made material will be launched, and thus added, to the near-Earth environment. Indeed, each time a mission is launched an abundance of "space garbage" is released: from aluminum fuel pellets to lens caps to experiment covers to experiment parts. These materials in turn create more debris as they float around and come in contact with other debris or spacecraft materials.

Once formed, space debris will form a toroid, or belt, around the Earth. Initially, an ellipsoidal cloud forms as the satellite or large debris chunk breaks up. This quickly evolves into an irregular, narrow torus. Eventually, the torus dismantles into a band about the Earth (Figure 1). The rate at which these phases are reached is dependent upon the altitude and inclination of the parent body and the velocity of impact.

The space debris encompasses a large range of sizes, from meters to microns, and is travelling with very high speed ( $\sim 8$  km/s, or 18,000 mph). Hence, collisions between orbital bodies can produce serious damage. The larger items ( $> 10$  cm) can be tracked by Earth-based radar allowing advance warning of potential collisions. For example, the Space Shuttle has suffered from delayed launches and has twice performed orbital evasive maneuvers in order to avoid large pieces of orbiting debris. However, even the smaller non-trackable

debris can cause potentially serious damage, witness impacts on the shuttle windows and heat tiles. A small piece of paint debris (a few thousandths of an inch) impacted the shuttle window causing a crater depth equal to one-quarter the window thickness.

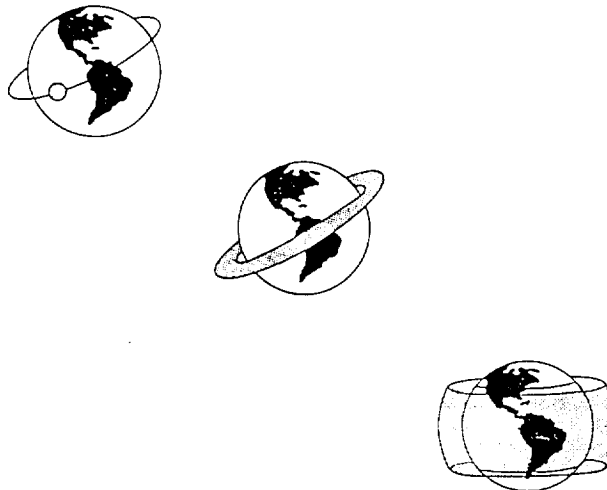


Figure 1: Schematic of satellite breakup debris cloud in near-Earth orbit.

With the continuing escalation of debris there will exist a definite hazard to unmanned communications satellites and especially to future manned operations, including Space Station Freedom. If not addressed, the growth of the space debris environment will lead to loss of satellites (e.g., telephone, communications, TV, weather) and could lead to the loss of astronaut lives.

Since the smaller non-trackable debris has the highest impact rate, it is clearly necessary to establish the true debris environment for ALL particle sizes. The best available method for tracking the smaller debris involves

observations of impact events on orbiting bodies.

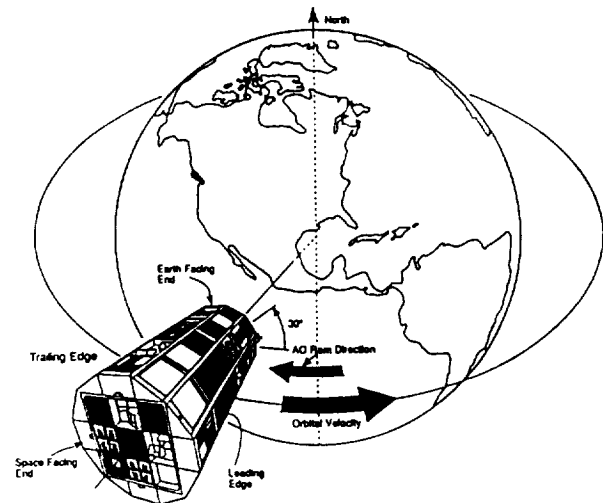
Such determinations are very important for assessing future and existing hazards. A proper understanding of the near-Earth space environment and its origin will allow and facilitate improvements in space operations and mitigation techniques thereby reducing both potential disasters and the costs of space operations.

The Long Duration Exposure Facility (LDEF) was designed as a reusable platform for launching and returning long duration (~1 year) space environment exposure experiments. This twelve-sided, closed cylinder platform was launched on April 7, 1984 from STS 41-C into a circular orbit about the Earth at an altitude of 450 km and orbital inclination of 28.4°. The satellite was gravity-gradient stabilized and flew its mission with one end constantly facing Earth and one side (Row 9) always facing into the RAM direction (Leading Edge; Figure 2). Post-retrieval analysis has shown that LDEF was slightly rotated, placing the RAM direction 7 degrees from normal relative to Row 9. LDEF was retrieved January 12, 1990 following a 5¾ year exposure period. The unforeseen delay was a result of the Challenger accident and mission scheduling. At the time of retrieval, the satellite's orbit had degraded to an altitude of 330 km.

The LDEF mission consisted of 57 separate experiments in 86 experiment trays with over 10,000 test specimens. Because of its exposure time and total exposed surface area, the LDEF provides a unique opportunity to characterize the natural and man-made particle populations in LEO. Previously, the most significant opportunities for this type of study were in the form of thermal blankets and thin aluminum membranes collected during the repair of the Solar Maximum Mission satellite.<sup>2</sup> In addition

to the micrometeoroid and debris environment, the LDEF revealed a wealth of information on the radiation, contamination, vacuum, atomic oxygen, and ultraviolet radiation environments in LEO.

In an effort to better characterize the near-Earth space environment, this study compares the results of actual impact crater measurement data and the Space Environment (SPENV)



**Figure 2:** Orientation of the Long Duration Exposure Facility (LDEF) in near-Earth orbit.

program developed in-house at POD, to theoretical models established by Kessler<sup>1</sup> and Cour-Palais.<sup>2</sup> Results of these efforts directly relate to the survivability of future spacecraft and satellites that are to travel through and/or reside in Low Earth Orbit (LEO) for long and short periods of time. In particular, these data are being used to (1) characterize the effects of the LEO micrometeoroid and debris environment on satellite designs and components, (2) update the current theoretical micrometeoroid and debris models for LEO, (3) help assess the survivability of spacecraft and satellites that must travel through or reside in LEO, and the probability of their collision with already resident debris, and (4) help define and evaluate future debris mitigation

and disposal methods.

#### METHOD

Data utilized in this study originated from three sources: (1) For craters larger than 0.05 cm diameter, measurements were taken by the LDEF Meteoroid and Debris Special Investigation Group's (M&D SIG) Kennedy Space Center Analysis Team on the entire LDEF aluminum structure.<sup>3</sup> (2) For craters larger than 0.003 cm diameter, measurements were taken by the authors from specific aluminum experiment sun shields, and (3) measurements from craters larger than 0.0001 cm diameter were taken by the Interplanetary Dust Experiment (IDE)<sup>4</sup> aboard LDEF during the first year of exposure. Since the latter data were only collected during the first year of flight, they were corrected for the full 5¼ year LDEF exposure time, by assuming no growth in the mean flux values. Separate environment models were utilized to make predictions for meteoroids and debris and compared to the SPENV model results. For meteoroids, the Cour-Palais *et al.*<sup>2</sup> model was used with the Kessler-Erickson velocity distribution as described by Zook.<sup>5</sup> For space debris, the Kessler model<sup>1,6</sup> was used. The SPENV program models both the micrometeoroid and debris environment that may be encountered by a spacecraft in an orbit between 200 and 2000 km.

#### SUMMARY

Hypervelocity impacts by space debris cause not only local cratering or penetrations, but also cause large areas of damage in coated, painted or laminated surfaces. Features examined in these analyses display interesting morphological characteristics, commonly exhibiting a concentric ringed appearance. Virtually all features > 0.2 mm in diameter possess a spall zone in which all of the paint was removed from the aluminum surface. These spall zones vary in size from approximately 2 - 5 crater diameters. The actual craters in the

aluminum substrate vary from central pits without raised rims, to morphologies more typical of craters formed in aluminum under hypervelocity laboratory conditions for the larger features. Most features also possess what is referred to as a "shock zone"<sup>2</sup> as well. These zones vary in size from approximately 1 - 20 crater diameters. In most cases, only the outer-most layer of paint was affected by this impact related phenomenon. Several impacts possess ridge-like structures encircling the area in which this outer-most paint layer was removed (Figures 3a, b). In many ways, such features resemble the lunar impact basins, but on an extremely reduced scale. Overall, there were no noticeable penetrations, bulges or spallation features on the backside of the tray. On Row 12, approximately 85° from the

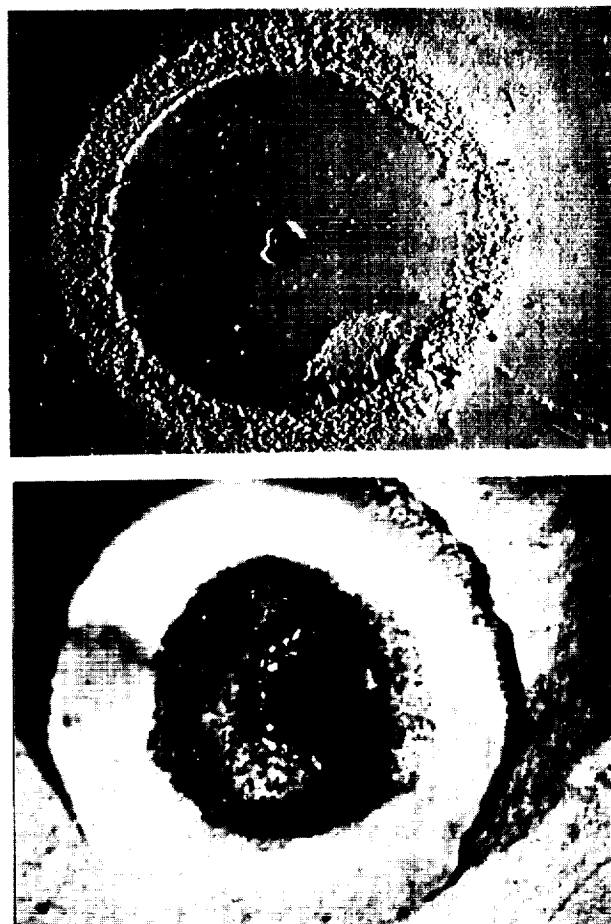


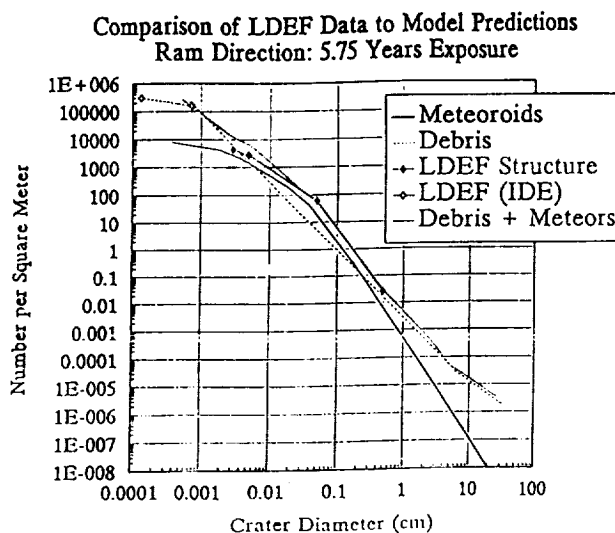
Figure 3:(a) rings, 5 mm across, crater 150  $\mu$ m.  
(b) attached dome 700  $\mu$ m, crater 200 $\mu$ m.

leading edge (RAM direction), there was approximately one impact per  $15 \text{ cm}^2$ . On the trailing edge, there was approximately one impact per  $72 \text{ cm}^2$ . Currently, craters on four aluminum experiment trays from Bay E09, directly on the leading edge are being measured and analyzed. Preliminary results have produced more than 2200 craters on approximately  $1500 \text{ cm}^2$  -or approximately 1 impact per  $0.7 \text{ cm}^2$ .

Figure 4 compares the predictions for the RAM direction from the meteoroid and debris models with the composite mean of the RAM-facing LDEF surfaces. The combined model predictions match relatively well with the LDEF data for impact craters larger than approximately  $0.05 \text{ cm}$  diameter; however, for smaller impact craters, the combined predictions diverge, or overpredict, from the LDEF data. The divergences cannot currently be explained by the authors or model

Cour-Palais micrometeoroid model underpredicts the mean flux for these small craters. Since this divergence is noted in all directions, including the Earth- and space-facing ends, the divergence may be indicative of either elliptical orbital particles from natural or man-made sources, of  $\beta$ -meteoroid fluxes, or a combination of the two. The IDE data has positively identified a  $\beta$ -meteoroid component of the natural environment, which is not currently included in the Cour-Palais model. It is unknown whether this  $\beta$ -meteoroid component can account for the entire divergence.  $\beta$ -meteoroids are small particles accelerated by solar radiation pressure that come from the direction of the sun.

One should be cautious in utilizing these comparisons to validate the micrometeoroid and debris models. The assumptions underlying this analysis are necessarily simplistic. For example, if the IDE mean flux data was assumed to have a growth rate (2%) identical to that used in the models, the IDE data would be 13% higher than shown in the figures. This increase would not solve the model divergence problem and could, in fact, complicate the problem even further. In addition, the IDE data is the only LDEF data which indicates the time dependence of the flux. While the data plotted here is for the IDE mean flux, the actual IDE data varies dynamically by as much as a factor of 1000 over time frames that vary from minutes to days. These time-dependent variations may be associated with toroids or clouds of debris impactors. Also, the IDE data indicates that most impactors were not in circular orbits, but were in elliptical orbits; this factor is also not included in the current models.



**Figure 4:** Comparison of LDEF data to theoretical model predictions

developers. More specifically, the Kessler debris model overpredicts the mean flux of small craters  $\sim 0.05 \text{ cm}$  diameter, while the

Lastly, there are many synergisms which have not been discussed here, such as erosion due to atomic oxygen, ultraviolet light, cosmic rays etc.. These phenomena, in concert with the impact damage, ultimately determine the useful

lifetimes of satellites or spacecraft.

#### CONCLUSIONS

The comparisons given here provide a good measure of the relative applicability of the models for first-order engineering design purposes, but illustrate the definite need for higher fidelity in the small impactor - spacecraft degradation - regime. This requires more data collection from space-based sensors, along with full analyses of data collected by ground-based and spec-based instruments. The LEO debris environment is a REAL problem that needs to be addressed. With the current debris growth rate of 5% per year expected to rise to 20% in the next few decades it is time to enact and follow adherrable space debris policies.

REFERENCES (1) Kessler, D.J., et al. (1987) NASA TM-100471. (2) Cour-Palais et. al. (1969) NASA SP-8013. (3) See T., et al. (1990) JSC#24608. (4) Unpublished data (1991) IDE Team: Institute for Space Science and Technology (5) Zook H.A. (1990) LPSC XXII, pp. 1385-1386. (6) Kessler, D.J., et al., 1990.

**GLOBAL SCALE CONCENTRATIONS OF VOLCANIC ACTIVITY ON VENUS:**

A Summary of Three 23RD LUNAR AND PLANETARY SCIENCE CONFERENCE Abstracts

**1. Venus Volcanism: Global Distribution and Classification from Magellan Data**  
*-L.S.Crumpler, Jayne C. Aubele, James W.Head, J.Guest, and R.S.Saunders*

**2. A Major Global-Scale Concentration of Volcanic Activity in the Beta-Atla-Themis Region of Venus**  
*-James W.Head, L.S.Crumpler, and Jayne C. Aubele*

**3. Two Global Concentrations of Volcanism on Venus: Geologic Associations and Implications for Global Pattern of Upwelling and Downwelling**  
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**SUMMARY**

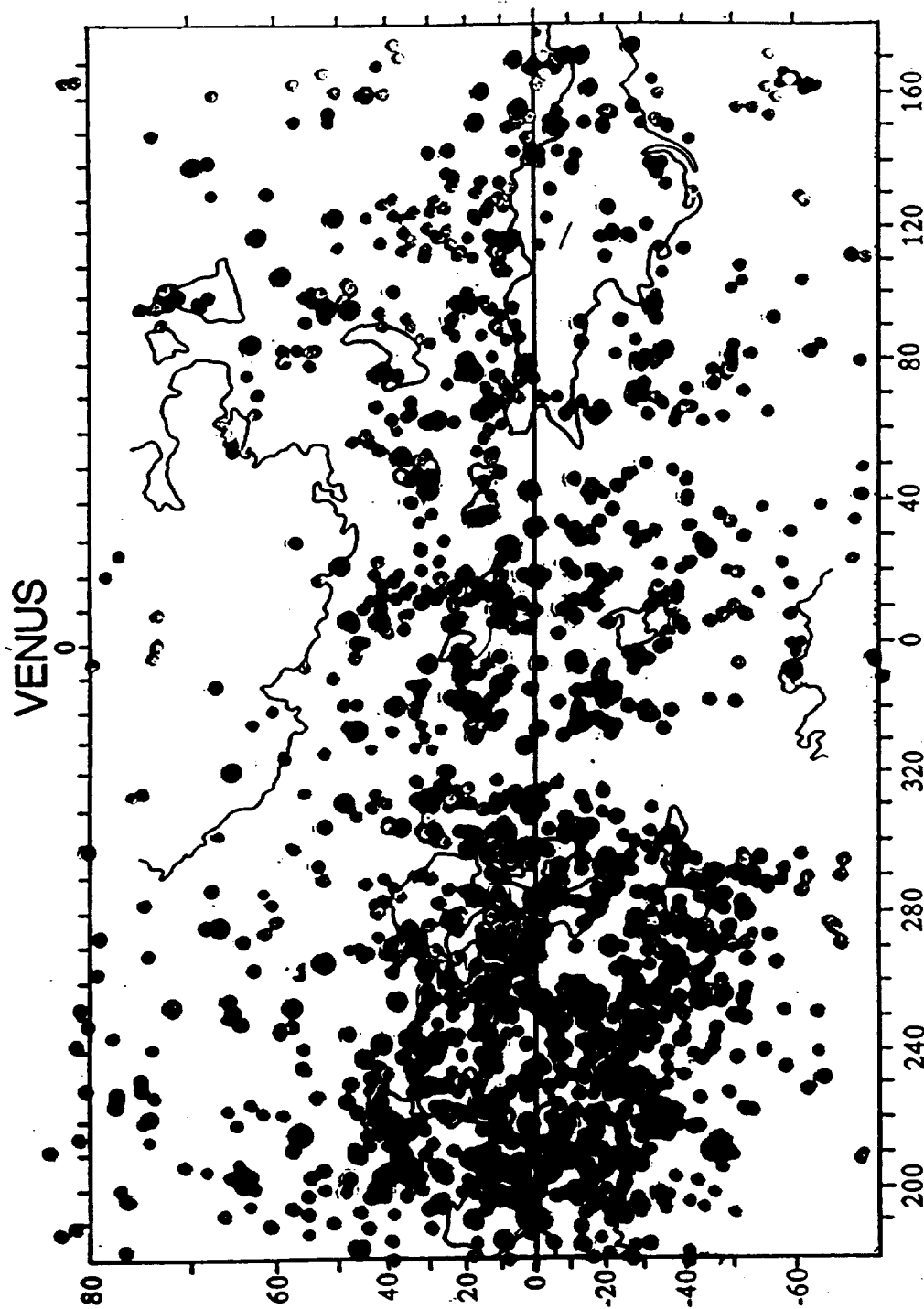
As part of the analysis of data from the Magellan mission, we have compiled a global survey of the location, dimensions, and subsidiary notes of all identified volcanic features on Venus [1,2]. More than 90% of the surface area has been examined and the final catalog comprehensively identifies 1548 individual volcanic features larger than ~20 km in diameter. Volcanic features included are large volcanoes, intermediate volcanoes, fields of small shield volcanoes, calderas, large lava channels, and lava floods as well as unusual features first noted on Venus such as coronae, arachnoids, and novae. A complete map of the location of all volcanic features and their relationship to the general geologic characteristics is important evidence about the global characteristics of Venus such as: how similar or dissimilar volcanism on Venus is to the other terrestrial planets, including Earth; the role of volcanism in the formation of crust and general geologic evolution of Venus; the main mechanism by which Venus losses heat (plate tectonics?, hot spots?, conduction?); how volcanically active Venus is; and how important lateral variations in mantle characteristics or mantle convection is in controlling the surface geological characteristics and distribution of volcanism.

In our analysis of Magellan data we show that one, and possibly two, large concentrations of volcanism occur. One prominent cluster in the area between Beta Regio, Atla Regio, and Themis Regio is approximately

the same size in relation to Venus as the large Tharsis volcanic region is in relation to Mars (about >20% of the surface area of each planet). Like the Tharsis region on Mars, these concentrations on Venus may be telling us about global scale lateral variations in the processes of volcanism, crustal formation, tectonism, and/or mantle convection. In addition to similarity with Tharsis, concentrations extending over hemispheric areas on Venus are comparable to hot spot clusters or superplumes on Earth. In all three cases, the global scale concentrations appear to correlate with global arrangement of geologic and tectonic characteristics in a manner that might represent large scale fundamental mantle anomalies or the effects of particular types of mantle convection thought to occur on Earth largely independent of the overlying lid associated with plate tectonics.

In addition to the distribution characteristics, the pristine condition of preservation of volcanic deposits on Venus should yield geological insights into the sequences of evolution associated with hot spots and their global influence on processes of crustal formation and evolution. Venus offers the most dynamic and varied opportunity yet to understand fundamental geologic processes that have influenced the geology of Earth.

**Figure.** Map showing the location of all volcanic centers on Venus based on survey of Magellan data.



MAGELLAN GLOBAL DISTRIBUTION OF VOLCANISM

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DURATION AND RATES OF DISCHARGE: MAJA VALLES, MARS.  
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SUMMARY: The 1600 km-long Maja Valles outflow system of Mars consists of three major divisions including the upper valley on Lunae Planum, the canyon section across Xanthe Terra, and the lower valley across western Chryse Planitia. Although, water released from the source in Juventae Chasma could reach the terminus of the present day valley system in central Chryse Planitia within 44 hours, the original outflow did not traverse the Martian surface in a direct path. It ponded along its course on northern Lunae Planum and near the western edge of Chryse Planitia significantly prolonging the lifetime of surface flow. Calculation of pond volumes and discharge rates through various parts of the channel system indicates that water flowed through this system for nearly a (terrestrial) year.

MAJA VALLES OUTFLOW: The Maja Valles outflow stretches from the 2 km deep, 100 km wide, and 250 km long box canyon of Juventae Chasma, on the northern edge of the Corpates Chasma, 1600 km northward into Chryse Planitia (Fig. 1). The outflow is traced as a broad, shallow valley marked by numerous flow features such as scour marks and streamline islands. Eleven hundred km from its source the flow ponded on the northeastern surface of Lunae Planum until the water rose to crest Xanthe Terra highlands to the east [1]. The water spilled eastward across Xanthe terra cutting a system of deep canyons (Bahram Vallis, Vedra Valles, Maumee Valles, and Maja Valles canyons). The outflow from these canyons ponded on the western edge of Chryse Planitia [2] before overflowing into northcentral Chryse Planitia. In addition to the two major sites of ponding, smaller local ponds were formed within breached craters and other natural depressions within the Xanthe Terra highland terrain.

POND VOLUMES: Whether Juventae Chasma represents a surface ponded source [3] or a basin formed by collapse during withdrawal of water from the subsurface [4], it is assumed that the volume of the chasma (62,500 cu. km) represents a minimum volume of water available to the upper Maja Valles channel. The impoundment on northern Lunae Planum is less well constrained but probably held approximately 15,000-20,000 cu. km of water. The pond on Chryse Planitia held approximately 4,000 cu. km of water. Various craters and depressions within Xanthe Terra held from 200 to 4,000 cu km of ponded water. Each impoundment requires time to fill and time to empty water along the outflow course; hence, each impoundment imparts a delay in that part of the flow that is routed through it.

## DURATION AND RATES OF DISCHARGE: De Hon R.A. and Pani E.A.

APPROACH: If, as in Maja Valles, a channel can be assumed to have been filled with water (bank-full discharge) during part of its lifetime and the slope over which the water was flowing is known, then it is possible to calculate the maximum discharge through the channel (in volume per unit time) using the Chezy equation (modified for Martian gravity). In similar fashion, if the configuration of an outlet and depth of water in a pond is known, the rate of discharge from the basin can be calculated assuming flow through a simple weir and spillway [3]. Thus, it is possible to calculate discharge rates from the various basins along the Maja channels and the maximum flow rates within the various channels. With this data, it is possible to place reasonable estimates of the minimum length of time required to drain the various impoundments and the duration of flow in various parts of the channel system.

RESULTS: Initial discharge from an impoundment is high because the water level (hence head) is high. As water is released from the basin, the head drops and the rate of discharges falls. The down stream channel carries a decreasing volume of water. Thus, a large part of the stored water is discharged rapidly, but the remaining water requires progressively longer intervals of time to be discharged from the source.

Initial calculations suggest that the Juventae Chasma source required 4 months to discharge, and that the Lunae Planum basin required 2 months to fill to capacity. Discharge from the Lunae Planum basin through as many as 15 outlets required as much as 8 months [3]. The Chryse Planitia impoundment probably filled to capacity and began to overflow after the first couple of months discharge from Lunae Planum. After which all further discharge from Lunae Planum crossed eastern Chryse Planitia unabated.

As the discharge from Lunae Planum decreased, many of the tributary channels across Xanthe Terra were abandoned, and flow became confined to the trunk valleys of Vedra and Maumee Valles. The Maja Valles canyon (across Xanthe Terra) was not opened until late in the outflow history, but once it was opened, it captured the remaining flow from the higher Lunae Planitia surface and channeled any later releases or water from along the upper Maja system.

A single release of water from Juventae Chasma could traverse the present channel system in about 44 hours, but the valley system did not exist when water was first discharged and basins were not emptied instantaneously. Thus a single release of water from Juventae Chasma was translated into a flow regime that spanned the better part of a terrestrial year. Subsequent releases from Juventae Chasma or other sources along upper Maja Valles may have kept flow through the channels active for an even longer time span.

## DURATION AND RATES OF DISCHARGE: De Hon R.A. and Pani E.A.

## SIGNIFICANCE:

- (1) Water flow through the valleys was a prolonged event and not an "overnight" affair. On geologic time scales, a year or two is a very short time span, but the current estimate is at least long enough to allow significant modification of the Martian surface by running water.
- (2) Because water ponded at several localities along the outflow system, sediments at each ponded site tend to be locally derived. That is, the sediments in any basin tend to be only from the nearest upstream basin. Thus, the various ponding sites will preserve a sedimentary record of the event, but the sediments may not be derived from great distances.
- (3) Because the discharge at the mouths on the canyons adjacent to Chryse received water from a variety of channel segments with differing holding times in local ponds, the erosional and depositional history at the mouths of the valleys is much more complex than the simple history of release of water from the source region.
- (4) Ancient lake beds provide excellent candidate sites for landing and rover missions because these surfaces tend to be extremely smooth and flat. (Bonneville Salt Flats in Utah is a not so ancient lake bed.) On the other hand, such plains may be extremely boring.
- (5) Outflow channels and lake basins are also prime candidate sites for the search for evidence of an early Martian biota.

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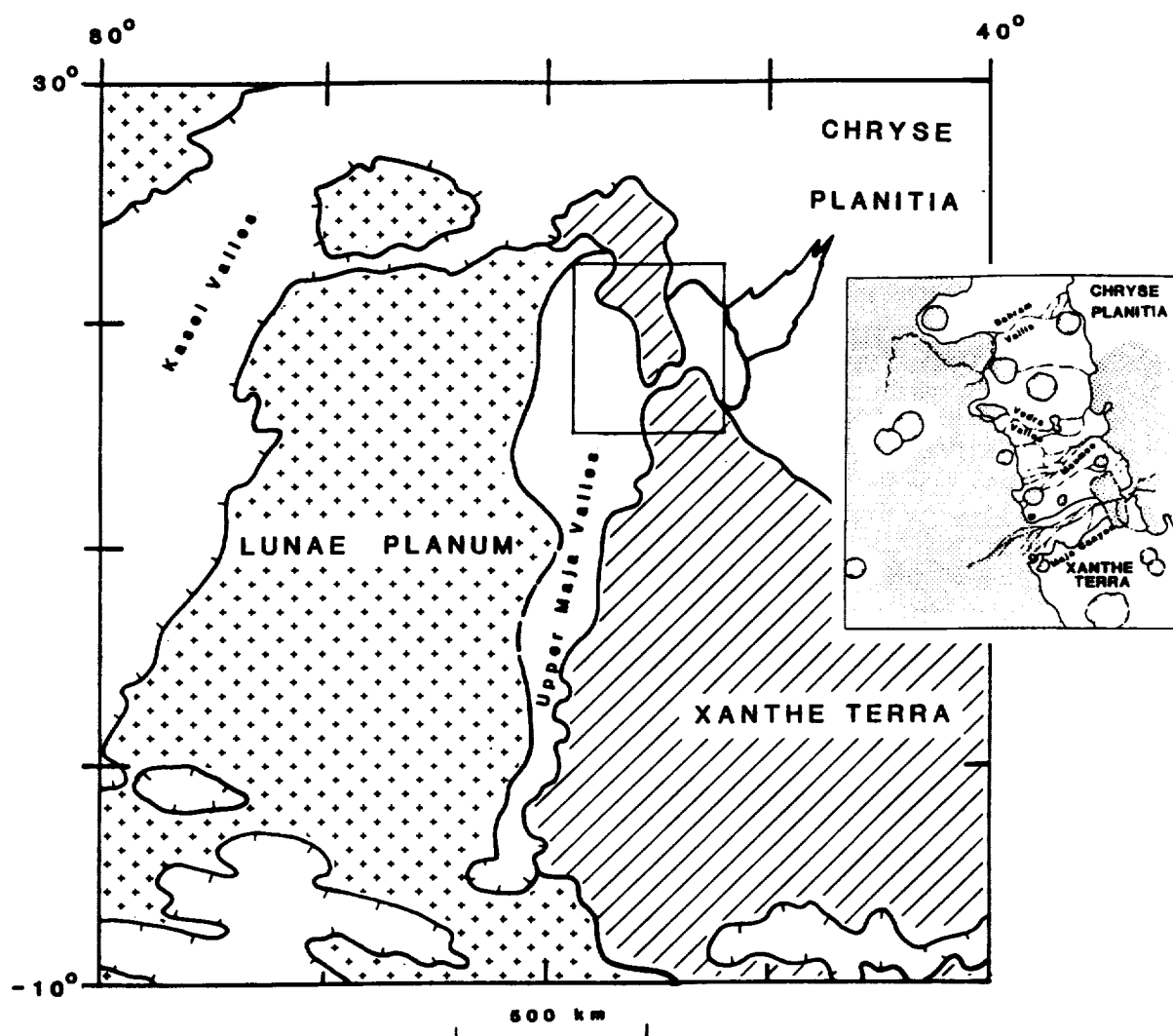


Figure 1. Overview of the Maja Valles outflow. Large impoundments formed on Lunae Planum and the western edge of Chryse Planitia. Inset shows a sketch map of valleys that drained from the upper impoundment (lake) on Lunae Planum to the lower impoundment on Chryse Planitia. Many smaller impoundments occur upon the irregular surface of Xanthe Terra.

**THE FIRST IDENTIFICATION OF A MAINBELT ASTEROID SOURCE FOR A METEORITE CLASS - E-TYPE APOLLO ASTEROID (3103) 1982BB: A LINK BETWEEN THE HUNGARIA ASTEROID ZONE AND THE AUBRITE METEORITES.**  
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In current models, the solar system is formed from a large cloud of interstellar dust and gas (the presolar nebula) which collapsed to form a flat disk with a central bulge (the solar nebula). The Sun formed from the central condensation while the dust grains in the disk accreted to form planetesimals (the asteroids, comets, and the meteorite parent bodies) which subsequently accreted to form the major planets.

The meteorites which fall onto Earth's surface are natural samples of solar system objects from outside the Earth-Moon system. Laboratory studies have shown that the meteorites preserve a record of the chemical and physical conditions which were present and of the sequence of events which occurred in the inner solar system prior to and during the formation of the major planets. It is believed that most meteorites are fragments of bodies which are located in the main asteroid belt between Mars and Jupiter and which have been preserved almost unchanged since the formation epoch.

Laboratory studies of the meteorites have provided a detailed "clock" of the conditions and processes during the accretion of planetesimals from the solar nebula and during the early evolution of the solar system. However the meteorites do not provide a good "map" to show where those conditions and processes occurred in the solar nebula and early solar system. This lack of an independent spatial context for the meteoritic data severely limits our ability to model the physical and compositional structure of the nebula and early solar system. One of the major goals of asteroid investigators has been to determine the source bodies of the meteorites, and thus to provide the needed spatial context. However, despite careful investigation of many of these asteroids, no specific mainbelt asteroidal parent bodies for particular meteorites have yet been identified.

The results reported here represent the first direct link of a set of meteorites (the aubrites or enstatite achondrites) back to a particular source region in the asteroid belt (the Hungaria zone of the innermost belt located at a heliocentric distance of about 1.9AU (1.9 times the Earth's distance from the Sun). Since most asteroids in the belt are still located near their original heliocentric formation distances, this link allows the

composition and temperature of the solar nebula to be determined at a specific distance from the Sun during the time of planetesimal formation.

The E-type asteroids have high albedos and featureless spectra which are interpreted as surface assemblages composed of an iron-free silicate mineral such as enstatite, forsterite, or feldspar [1-3]. It has been generally believed that the E-class asteroids are analogous to (and perhaps even genetically related to) the enstatite achondrites (aubrites). These meteorites are the crust and/or mantle fragments of a parent body with a very low oxidation state (analogous to the enstatite chondrites) which underwent melting and efficient differentiation to produce a silicate crust and a nickel-iron core [4]. Because of the high melting temperature of enstatite, the E-asteroids and the aubrite parent bodies must have experienced extremely strong heating subsequent to planetesimal formation.

From its relatively neutral colors, the Apollo object (3103) 1982BB was originally classified as an X-type (E, M, or P) asteroid [5]. Determination of its high albedo (0.53-0.63), removed the ambiguity and identified it as taxonomic type E [6]. Reflectance spectra (0.8-2.5 $\mu$ m) of 1982BB were obtained using the NASA Infrared Telescope on Mauna Kea on July 18-20, 1991UT. Figure 1 shows that the weak 0.89 $\mu$ m feature seen in the spectrum of the mainbelt E-asteroid (44) Nysa due to a trace content of iron in the enstatite [2] is absent in the spectrum of 1982BB, and no other discrete mineral absorption features are seen. The lightcurve amplitude (0.9 mag) is similar to that reported previously [5,7], and good spectra were obtained for both lightcurve maxima. There are no detectable spectral differences between the opposite faces observed at the two lightcurve maxima.

Apollo asteroid (3103) 1982BB is a high albedo E-type object with a reflectance spectrum consistent with the iron-free silicates, primarily enstatite, present in the enstatite achondrite meteorites. The correlated variation [8] of the visible [5] and thermal infrared lightcurves [6] indicate that it is an elongated object with no substantial surface albedo variations. Apollo asteroid (3103) 1982BB is presently in an orbital resonance (3:5) with the Earth, and appears to be a relatively long-lived member of the Earth-approaching population [9].

Since it is probable that a significant portion of the meteorite flux is derived from intermediate Earth-approaching parent bodies, we evaluated the possibility that (3103) is the sole or primary near-Earth parent body of the aubrites. Several lines of evidence support the interpretation that

(3103) 1982BB is the actual near-Earth parent body of the aubrite meteorite class, and not merely a reasonable candidate among the known Earth-approaching asteroids:

- (1) (3103) 1982BB is the only identified E-type object within the near-Earth population, and consideration of discovery biases suggests that there cannot be many kilometer-sized E-type objects within this population.
- (2) The clustering of exposure ages and mineral compositions [4] suggests that most aubrites are derived from a single parent body.
- (3) The time-of-day of aubrite falls indicates a limited range of source orbits, which are similar to that of asteroid (3103). Given the rarity of E-types in the near-Earth population, it seems unlikely that many other comparable sized E-objects could be in similar orbits.
- (4) The long aubrite cosmic ray exposure ages compared to other stony meteorites suggests that for much of the time in space prior to falling to Earth, they were not small meteoroids but were probably stored on the surface of an intermediate parent body such as a near-Earth asteroid.
- (5) The cosmic ray exposure ages of the aubrites would require that any near-Earth parent body be in a relatively long-lived orbit with a low regolith gardening rate similar to that of 1982BB.
- (6) A significant portion of the aubrite falls appear to derive from one or two meteoroid streams. A near-Earth source for any such stream is likely.
- (7) Two of the nine aubrite falls occurred at the descending node of the orbit of (3103) suggesting a direct link.

It therefore seems probable that most of the aubrites are fragments of Apollo asteroid (3103) 1982BB. It also appears probable that (3103) was derived from the Hungaria region at the innermost edge of the asteroid belt. The orbital inclination ( $20.9^\circ$ ) and aphelion distance (1.905AU) of (3103) 1982BB falls within the Hungaria zone (mean:  $a=1.90\text{AU}$  and  $i=28^\circ$ ; 80% limits:  $1.79\text{AU} < a < 1.98\text{AU}$  and  $15^\circ < i < 40^\circ$ ) as shown on Figure 2. In considering whether (3103) was derived from the Hungaria zone, we have focused on two issues: (a) whether effective mechanisms exist to convert a Hungaria-type orbit into a (3103)-type orbit, and (b) whether there is physical evidence linking (3103) to the Hungaria region of the asteroid belt.

The velocity change needed to convert a circular 1.905AU Hungaria orbit into that of (3103) is approximately 3.0km/sec. The lunar meteorites prove that some coherent material could be sufficiently accelerated by an impact event [10]. However, the size limit on coherent rocks impact accelerated to 3km/sec is 0.03-0.3 meters [10], so it does not seem probable that an object as large as 1982BB (1.5 km) could be accelerated by 3km/sec by a single impact. The Hungaria zone is bounded by the  $v^{16}$

resonance which has a chaotic zone [11] that could serve to convert injected Hungaria fragments into Earth-approaching orbits similar to that of (3103). The impulse required to move an average Hungaria ( $a=1.90\text{AU}$ ) into the  $\nu^{16}$  resonance ( $a=2.08$  at  $i=25^\circ$ ) is  $1\text{km/sec}$ . It seems probable that a significant number of Hungaria collisional fragments are converted into planet-crossing orbits via the  $\nu^{16}$  resonance, and that they constitute some component of the Earth-approaching population.

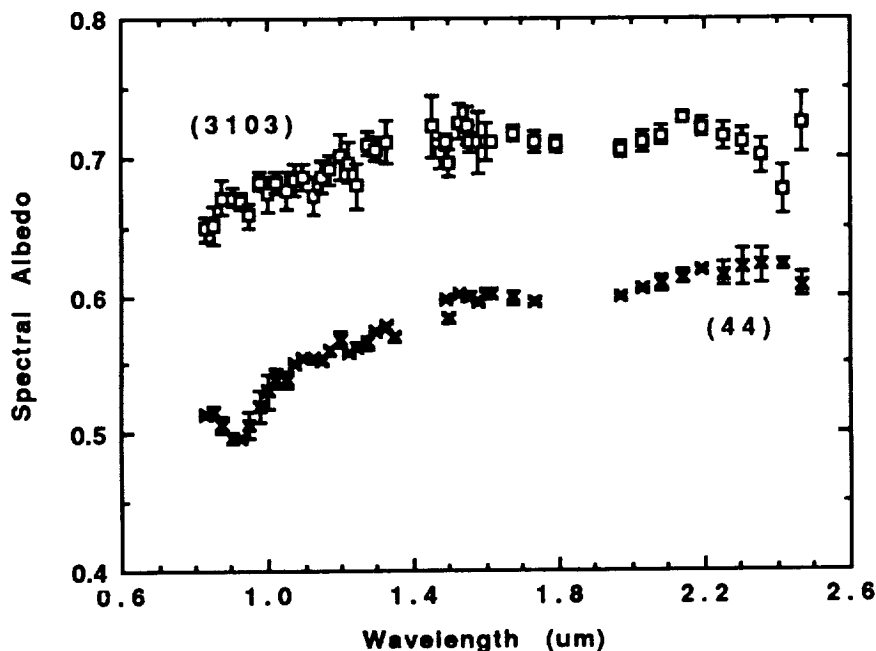
Orbital considerations suggest that (3103) could be derived from the Hungaria zone. However, the spectral type of (3103) makes such a source probable. The Hungaria zone is the only region of the asteroid belt where E-type asteroids are common [12]. E-type objects constitute about 55% of the classified Hungaria population. Although a more detailed investigation of the dynamical evolution of this object is needed, it appears highly probable that (3103) 1982BB was derived from the Hungaria region of the innermost asteroid belt, that it is a fragment of the collisional breakup of an E-object near  $1.9\text{AU}$ , and escaped the mainbelt via the  $\nu^{16}$  resonance. This represents the first direct linkage between a meteorite type and a mainbelt source region.

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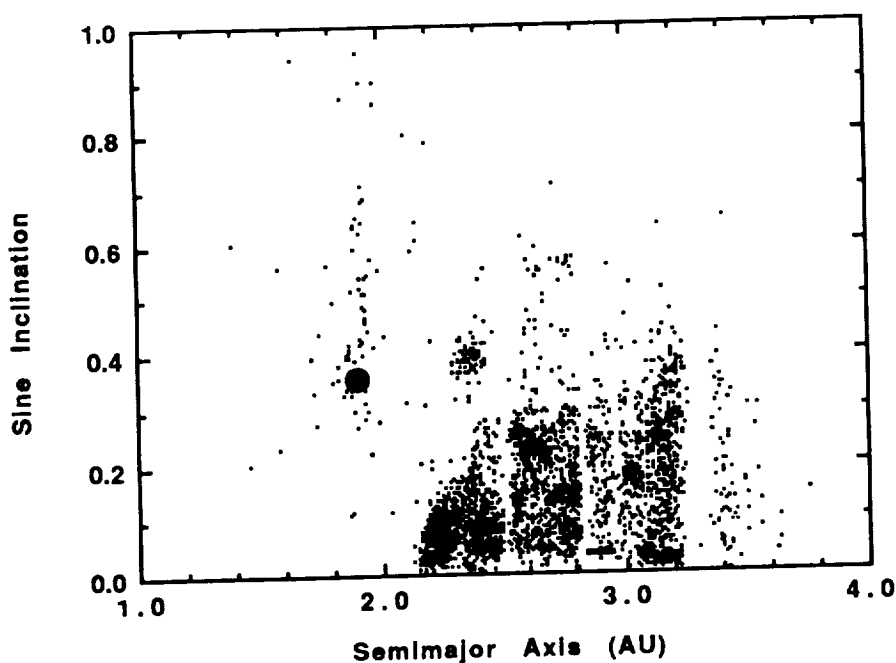
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**Figure 1:** The visible and near-infrared spectral albedo of (3103) 1982BB compared to that of the the mainbelt E-type asteroid (44) Nysa. The albedos of these objects are comparable to snow.



**Figure 2:** The location of the aphelion point of (3103) 1982BB [indicated by the large filled circle near  $a=1.9$  AU and  $\sin i = 0.35$ ] is compared to the proper orbital elements of the known asteroids [11]. The Hungaria zone, which is the innermost portion of the asteroid belt, is the cluster of points located near semimajor axis = 1.9 AU and sine inclination = 0.2-0.6.



**<sup>146,147</sup>Sm-<sup>142,143</sup>Nd SYSTEMATICS OF EARLY TERRESTRIAL DIFFERENTIATION AND THE LOST CONTINENTS OF THE EARLY EARTH**

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The *very early history of the Earth* has been one of the great enduring puzzles in the history of geology. James Hutton, in what was subsequently to become the most famous dictum in geology, concluded a 1788 summary of the state of knowledge in geology with the judgement that the geological record contained "no vestige of a beginning" [1]. It is true, if rather surprising, that the subsequent two centuries of research in the Earth sciences have done essentially nothing to alter the veracity of Hutton's statement. What has changed, due to insights from modern plate tectonics and the Apollo program, is that reasons for this famous absence of evidence are now well understood. The search for *vestiges of a beginning* in the geological record now involves efforts to measure exceedingly minute effects in the nuclear composition of certain key trace elements found in very old rocks, and the kind of scientific sleuth work required is far removed from that employed in the days of Hutton, because, as we shall see, the geological record is nonexistent for the period of interest that we are investigating.

Here we report evidence which clearly can be described as a vestige of a beginning, because the evidence that we report cannot be interpreted in any other way except as a geochemical signal of processes active in the very early history of the Earth. The evidence itself is a very small "anomaly" in the abundance of one of the isotopes (mass-142) of the rare earth element neodymium (Nd), due to the decay of a now-extinct radionuclide of the rare earth element samarium: <sup>146</sup>Sm. <sup>146</sup>Sm was present initially at the beginning of solar system history with an abundance of only about 0.025% of Sm, and it decayed thereafter with a half-life of 103 million years. After 5 half-lives, it would have been effectively "dead." Hence any anomaly measured in the Earth is evidence for a preserved record of geochemical differentiation (such as crust formation) which took place within the first 500 million years of Earth history.

Firstly, however, a disclaimer must be made that the origin of the Earth, *per se*, is actually not where the epistemological lacuna in the geological record lies, and it is not the subject of our study. The existence of the Earth's core is a very well known basic fact of modern seismology, and its formation was probably a direct consequence of the energetics of accretion. So, in a sense, the Earth's core is a vestige of the Earth's origin. Moreover, a new dating technique, <sup>182</sup>Hf-<sup>182</sup>W, has been developed recently by one of us (CLH) [2], which can date the epoch of accretion and core formation very precisely. (Preliminary study suggests that the Earth's core formed contemporaneously with accretion.) There also exists a considerable literature on the origin of the Earth and formation of its core by planetesimal coagulation; some models appear to be on the right track toward modelling the accretion of the Earth (and also provide a plausible explanation the origin of the Earth's moon via mass ejection from a giant impact). These are all very interesting topics, and it is clear that considerable scientific progress has been made since the time of Hutton! But in this study, we are not primarily concerned with the formation of the Earth and its differentiation into a silicate mantle and metallic core.

The unmapped *terra incognita* of Earth's history which concerns us is the "Hadean" era. The Hadean encompasses the first ~600 million years following the origin of the solar system 4.57 billion years ago, and is defined as that period of geological time for which there is no surviving evidence in the geological (*viz.*, crustal) record. (At present the Earth's oldest rocks are the Acasta gneisses of the Slave Province, Northwest Territories, Canada, which have been dated by zircon U-Pb systematics to  $3962 \pm 3$  Ma [3]. Other, slightly younger ancient crustal exposures have been identified at Isua, west Greenland [4], Uivak, Labrador [5], and Mt. Sones, Enderby Land, Antarctica [6].) The Hadean has been subdivided on the basis of lunar stratigraphy [7], but for the Earth itself, the Hadean is the epoch for which no known crustal sections survive. No trace of primary crust remains, and the oldest known surviving crustal

materials --a trace population of zircons in Western Australian sediments-- date only to ~350 Ma after the initial accretion of the planet [8]. All of the oldest known crustal regions are put together sum to well below 1% of the volume of existing continental crust today. So if we have some reasonably secure ideas about the earliest epoch of terrestrial accretion and core formation, the Earth has clearly kept up a vigorous defense against all would-be parties to the secrets of her first 600 million years. It is clearly not for want of scientific effort that nothing is known about the terrestrial Hadean; geological processes have very efficiently wiped the slate clean.

Why then did so little very old crust survive? One answer to this question is apparent by looking at the surfaces of the Moon, Mars and Mercury, all of which exhibit terrains saturated in impact craters, --the so-called "ancient cratered terrains." These terrains are regoliths which have been repeatedly shocked and blasted and reworked by impacts such that the crust is basically a pile of heavily shocked rubble. Dating of lunar breccias and photogeological crater stratigraphy studies indicate that heavy cratering persisted on the moon until about 3.85 billion years ago. One conservative estimate for cratering on the Earth during the interval from 4.44 to 3.85 billion years suggests the formation of over 200 giant multi-ring basins (>1000 km in diameter), with much greater numbers of smaller crater-forming impacts [9]. Hence the surface of the Earth during the first several hundred million years will have been battered by impacts and, as one well known researcher has put it, early crust "grew in the teeth of this barrage"[10]. Erosion would have made short work of the very early terrestrial crust, and it is therefore not surprising that no pre-4 billion year old crust survives. Indeed, an interesting speculation is that the oldest surviving crustal areas are in fact the result of impact-generated crust formation related to the "terminal heavy bombardment" recorded on the Moon [17].

The other answer to the question of why so little very old crust survives is apparent simply by looking at any of the famous views of the Earth taken from space. The Earth's surface exhibits a very low density of impact craters, whereas all ancient (*i.e.*, older than 4 Ga) surfaces in the solar system are heavily cratered. The Earth has no heavily cratered terrains, hence all terrestrial surfaces are relatively young; *ergo* the Earth has been a geologically active planet throughout its history. Thus the Earth, like its sister planet Venus, and unlike Mars (which is much smaller and nearly cold and geologically "dead," like the Moon), is very much a geologically active planet; it is large enough for its mantle to retain enough heat for there to be a viscosity-controlled equilibrium between radiogenic heat production and mantle convective heat loss. Because the Earth is hot enough to support solid state convection on a large scale, mantle convection has acted over the entire history of the Earth to keep upper mantle temperatures near to the melting point (the "solidus"). At temperatures near the solidus, small increases in temperature lead to proportionally very large decreases in bulk viscosity. A more viscous mantle will convect faster, and consequently increase its rate of heat loss due to convective transport of heat to the surface, thereby lowering its temperature. Such a situation is described as "buffered," and, because there was more radiogenic heat production at early times, we can be sure that mantle convection has been active throughout Earth history. Indeed it clearly will have been more vigorous in the past. The Earth's silicate mantle has therefore always been mobile, and over most of Earth history has supported a tectonic cycle for its frozen surface crust. In the present epoch, this cycle destroys old material while at the same time building up new terrains and welding them together into continents. Old continental crust is uplifted by the forces of global tectonism, while on surfaces, rain, wind, chemical dissolution and freeze-thaw cycles all work away on relatively brief geological timescales to break-up and reduce exposed rocks down to sediment. Eventually, crustal sediment is subducted at trenches and reentrained into the mantle circulation and rehomogenized. The overall process of crust production, subduction and convective stirring into the mantle is known as *crustal recycling*. It affects continental crust via erosion and sedimentation, and also by lower crustal "delamination" under subduction zones. Plate tectonics has probably been active on Earth for at least 4 Ga [11], and it is therefore not surprising that only a trace of very old crust survives; most old crust will have been recycled. However, isotopic evidence suggests that the contemporary style of plate tectonics may well not

have been active prior to ~4 billion years ago. Had it been, it is perhaps unlikely that the effect reported here would have survived rehomogenization due to plate tectonic recycling of old crust back into the mantle. In addition, the earliest crust of the Earth may well have been quite different from modern day oceanic and continental crust.

So we understand why it is that the face of the Earth has changed drastically through geological time. Under the present tectonic regime, older crust is progressively erased by erosion and recycling. What did the Earth look like over 4 billion years ago in the Hadean? Were there early continents? If so, were they similar in composition to present-day continents, or were they more mafic in composition, like contemporary Iceland, the southern highlands of Mars, or the basaltic continents of Venus? Whatever they were like, they are the *lost continents of the early Earth*. The primary aims of our present study have been (i) to verify the existence of these "lost continents", and (ii) to determine their mean age.

Obviously, it is not possible to reconstruct the appearance of lost terrains. However, isotopic systematics allow one to quantify the fraction of continental crust (relative to the present day volume) existing in the past at different times. Thus far, the application of isotopic systematics to the study of crustal evolution in the very early Earth has been limited by both the absence of samples from Hadean times and uncertainties in the interpretation of isotopic signatures in very old rocks, often resulting from the long and complicated metamorphic histories of most ancient crustal sections. The aim of this study has been to develop a new method of quantifying the production of crust on the Earth which "sees through" metamorphic effects and focuses specifically upon the critical Hadean period in the very early history of the Earth. To achieve these ends, we have been investigating a powerful coupled systematics based upon the decays of two unstable nuclides of the "parent" element samarium (Sm) to two "daughter" nuclides of the element neodymium (Nd). (The technical details of the interpretation of the coupled Sm-Nd systematics are given in our LPSC XXIII abstract.) The critical effect to measure in the coupled systematics (a " $^{142}\text{Nd}$  anomaly"), is very small and is described as a deviation in parts per million (ppm) in the  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio of a sample relative to that measured in a laboratory standard. New developments in the technology of very high precision mass spectrometry (the technique used to measure isotopic ratios in elements separated from rock samples) have made these measurements possible.

Radiogenic isotope geochemistry [12] is a science which investigates the evolution of isotopic ratios (such as  $^{143}\text{Nd}/^{144}\text{Nd}$ ) in time, in which the numerator mass is usually the decay product isotope, and the denominator mass is a stable reference isotope. The growth in such a ratio is a function of the decay rate of the parent and the parent to daughter ratio (Sm/Nd in our case) at any given time. Because the measured isotopic composition of a daughter element in a rock records the time-integrated history of the decay of its parent element throughout geological time, it is possible to obtain well-defined constraints on the parent to daughter element ratio of the source reservoir (or reservoirs) of that rock. These constraints tell us about the geochemical fractionation history of the Earth's crust and mantle; in our case the history of Sm/Nd fractionation with respect to the initial ratio in the Earth, (which is known from measurements of Sm/Nd in primitive undifferentiated meteorites). Crust is formed by melting, and melting in general leads to a fractionation in the Sm/Nd ratio of both the source and the extracted melt. While an alternate explanation exists for Sm/Nd fractionation within the mantle ("mantle stratification"), the isotopic evidence that we present for Sm/Nd fractionation in the early Earth most probably indicates melt extraction to form crust. Another consideration is that if crust is efficiently recycled back into the mantle on a short time scale, then the mantle will not carry the time integrated isotopic signature of melt extraction / crust formation. The isotopic signature of the upper mantle reflects a balance between the opposing processes of melt extraction and crustal recycling. Hence isotopes also tell us about the history of the destruction of crust as well, and if at any time the mantle carries a signature of melt extraction, it tells us that at that time there had been a net cumulative transport of crust out of the mantle. Having surveyed these preliminaries, we now turn to the specifics of our discovery.

One of the decays in the new coupled Sm-Nd systematics,  $^{147}\text{Sm}$  to  $^{143}\text{Nd}$ , has a half-life of 106 billion years and therefore is 'active' throughout all of geological time. The  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  systematics are a well known technique in geochemistry and have been used in numerous dating and tracer studies since the development of the technique in the early '70s. One of us (SBJ) has shown that the history of crustal evolution and recycling in the Earth can be inferred from the geological record of  $^{143}\text{Nd}/^{144}\text{Nd}$  isotopic evolution [13]. The other decay,  $^{146}\text{Sm}$  to  $^{142}\text{Nd}$ , has a half-life of 103 million years, and therefore was 'active' only during the first few hundred million years of Earth history, after which it became effectively extinct. The  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics are a relatively little-known technique. In the early 80's, one of us (SBJ), then working with Jerry Wasserburg at CalTech, found evidence for the decay signature of  $^{146}\text{Sm}$  in two meteorites that were samples of 4.55 and 4.46 billion year old asteroidal crusts [18]. The application of the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  systematics, until recently, has been limited to the dating of meteorites. One of us (CLH), working with Larry Nyquist of the NASA Johnson Space Center, has shown that  $^{142}\text{Nd}$  anomalies exist in Martian and lunar rocks which are far too young for  $^{146}\text{Sm}$  to have been present in sufficient abundance to generate an anomaly [14]. (The "SNC" meteorites are very probably from Mars, and are thought to have been ejected from the Martian surface by one or more oblique impacts. Impacts also bring lunar rocks to Earth as "lunar meteorites.") Instead, what the anomalies tell us is that these rocks were extracted from a fractionated source reservoir that formed very early in the planet's history. In the Moon, this result was expected because it was well known that the major episodes of differentiation on the Moon all predated 3.8 billion years. However, the Martian record is inferred from only a very small number of meteorites (presently 9), and in the Martian rocks the anomaly was very interesting because it indicated that the melts had been extracted from the Martian mantle within no more than ~100 million years of the origin of the solar system. Indeed, this result is consistent with the existence of the ancient cratered southern highlands of Mars, which are probably basaltic in composition and on the basis of cratering statistics are thought to have formed within the first few hundred million years of Mars history.

What about the Earth? Did it once preserve ancient cratered highlands? The discovery that we are presenting for the Earth suggests that it did. The discovery is a  $^{142}\text{Nd}/^{144}\text{Nd}$  anomaly in a rock from the Isua supracrustals of western Greenland. It's sign is the same as that for the anomaly found in the Martian rocks. Earlier studies of this and related rocks at Isua by one of us (SBJ) [16] have shown that initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios in the Isua rocks 3.8 billion years ago indicate that the mantle at that time had already experienced a long time-integrated history of net extraction of melt. In simple terms, this means that a relatively large crust probably existed on the Earth four billion years ago, and, according to isotopic modelling, it's volume was probably ~40% of that of the present day continents. However, prior to the development of the new method, it was not possible to determine the age of the missing crust. Our discovery employing the new coupled systematics allows us to determine the mean age of this "lost" Hadean crust. At present, the uncertainty on the anomaly measurement is large ( $+39\pm 26$  ppm, at 95% confidence), but it clearly indicates a very old mean age of  $\sim 4.5\pm 0.2$  billion years for this crust. Any crust of this age will have been a cratered highlands regolith, but possibly mixed together with large volumes of impact melt and basalt flows generated by catastrophic upwelling of mantle to fill the transient cavities excavated in impacts. *So there were lost continents on the early Earth.* But they probably looked more like the surface of the moon than anything seen in the present day continents!

**IMPORTANT NOTE:** At the time of the writing of this abstract, we are engaged in efforts to reproduce our measurement by means of different cup configuration in the mass spectrometer, which is also expected to allow a substantial increase in precision. *Following the usual scientific procedure, the reality of the anomaly discussed in this abstract is subject to this effort*

at verification, which is in progress. Results for these experiments will be available at the Lunar & Planetary Science Conference.

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**Presolar (?) Corundum in the Orgueil Meteorite.**

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The discovery in chondritic meteorites of diamond, SiC, and poorly crystallized graphite that formed around other stars [1-3] demonstrated conclusively that presolar dust survived the formation of the solar system to be incorporated into meteorites. The presolar nature of these grains is shown by the highly unusual isotopic compositions of their constituent elements. To date, all recognized types of presolar grains have been carbon rich and apparently formed around carbon stars, those with  $C/O > 1$ . We report here the discovery of the first oxygen-rich grain with isotopic characteristics consistent with a presolar origin. Oxygen-rich grains presumably form only around stars with  $C/O < 1$ .

Detailed isotopic studies of presolar grains are beginning to provide insight into the synthesis of the elements in various types of stars. Isotopic characteristics indicate that each type of carbon-rich presolar grain formed around a different type of star. Diamonds seem to be associated with supernovae [1,4], SiC with red-giant stars [5], and graphite perhaps with novae [3]. The isotopic variability among grains of the same type suggests that more than one star was involved in the production of each type of grain [5-7]. Since carbon stars do not produce as much interstellar dust as do oxygen rich stars [e.g., 8] and since carbon rich dust is less abundant in interstellar space than is silicate dust [e.g., 9], oxygen-rich dust should have dominated the mix in the sun's parent molecular cloud. The discovery of a presolar oxide grain gives us our first glimpse of this vast reservoir of oxygen-rich dust. As more grains are recognized and characterized, we should be able to make inferences about nucleosynthesis in oxygen-rich stars.

If meteorites inherited the average mixture of presolar dust from the sun's parent molecular cloud, why have we not seen lots of presolar oxides or silicates before now? First, diamond, SiC, and graphite were discovered and isolated because of the strange noble-gas components that they carry, and these three minerals apparently explain the known anomalous noble gases. Thus there

is no tracer of presolar oxides or silicates that can be detected in bulk samples to guide a search. Second, the chemical procedure developed to isolate presolar diamond, SiC, and graphite is designed to remove the silicates, metal, sulfides, and reactive oxides so as to isolate the carbon-rich phases. Therefore, all experiments to date have thrown away most of the candidate oxide or silicate material before it could be examined. Third, the solar system is an oxygen-rich environment. Carbon-rich materials like diamond, SiC, and graphite, are not likely to form in the solar system so there is little 'local' material to confuse searchers. In contrast, silicates and oxides are the expected products of solar-system processes. From 50–85% of most chondrites consists of chondrules, metal, and troilite that is clearly of 'local' solar system origin. Much of the remaining material may be 'local' as well. Thus, there is a lot of 'noise' to hide the presolar signal. Fourth, aqueous and/or thermal alteration of the original material from which the meteorites formed is universal among chondrites. Refractory diamonds and SiC can survive mild thermal metamorphism and aqueous alteration, but the dominant oxygen rich material may be amorphous silicate [9], which is easily destroyed by aqueous alteration. Thus much of the original oxygen-rich dust, as well as much of the carbon-rich organic material, may have been altered beyond recognition by parent-body processes.

Our search for oxygen-rich presolar grains has been designed to overcome these problems. In the initial phase, we avoid problems two and four by looking at oxide minerals that survive the acid treatments used to isolate diamond and SiC, such as corundum, hibonite, and spinel. Such minerals would also survive aqueous alteration and mild thermal metamorphism. To minimize the 'noise' problem, we chose to look first in an acid residue from the Orgueil (CI) carbonaceous chondrite, whose abundances of diamond, SiC, and graphite suggest is composed entirely of the 'matrix' material that contains presolar grains [10]. Because we have no 'tracer' to guide mineral separations, we use the ion probe, which can analyze individual micron-sized mineral grains in a mixed residue.

Ion probe work on diamond, SiC, and graphite has shown that presolar grains can have extremely unusual isotopic compositions in their Si, C, and trace elements such as Mg [6, 11, 12].



Mg was chosen as our initial target for ion probe measurement because of the relative ease of measurement and because of the potentially large isotopic variations that might be expected in a presolar grain. Mg has three isotopes and there are two kinds of isotopic effects that would demonstrate that a grain is presolar. First,  $^{24}\text{Mg}$  is produced by different nucleosynthetic processes than are  $^{25}\text{Mg}$  and  $^{26}\text{Mg}$ , so one might expect that the relative proportions of the two types of Mg would differ in products from different nucleosynthetic environments. Second,  $^{26}\text{Mg}$  is the daughter of radioactive  $^{26}\text{Al}$ , which has a half life of 720,000 and thus decays away within about 10 million years after it is produced in stars. Although  $^{26}\text{Al}$  apparently existed in the early solar system, the inferred  $^{26}\text{Al}/^{27}\text{Al}$  for this early epoch is low, around  $5 \times 10^{-5}$ . Theoretically, the production ratio of the two Al isotopes can approach 1 in certain types of stars, and studies of circumstellar SiC and graphite have shown that Al with a  $^{26}\text{Al}/^{27}\text{Al}$  ratio of up to 0.1 can be incorporated into grains formed in stellar atmospheres [6]. We therefore look for either a significant anomaly in the relative abundances of  $^{25}\text{Mg}$  and  $^{26}\text{Mg}$  with respect to  $^{24}\text{Mg}$ , or a very large excess of  $^{26}\text{Mg}^*$  (from the decay of  $^{26}\text{Al}$ ) in minerals with high Al content.

We measured Mg isotopes in 24 spinel grains, 5 hibonite grains, and 22 corundum grains from our Orgueil residue. No evidence was seen for an anomaly at  $^{24}\text{Mg}$ . However, two corundum grains exhibited huge  $^{26}\text{Mg}$  excesses, with  $^{26}\text{Mg}$  abundances 36.5 (Grain A) and 11–14 (Grain B) times those of normal Mg. These large excesses in grains with very low absolute Mg content result from the decay of  $^{26}\text{Al}$ . After subtracting the normal  $^{26}\text{Mg}$  present in the sample (by assuming a normal  $^{26}\text{Mg}/^{24}\text{Mg}$  ratio), the remaining  $^{26}\text{Mg}^*$  can be scaled to total Al in the sample to give the  $^{26}\text{Al}/^{27}\text{Al}$  ratio at the time of grain formation. For Grain A, the initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio was  $5.3 \times 10^{-5}$ , very similar to ratios inferred for calcium-aluminum inclusions (CAI) and consistent with a solar system origin. The initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio for Grain B was  $9 \times 10^{-4}$ , a value 18 times higher than has been observed in solar system material! The  $^{26}\text{Al}/^{27}\text{Al}$  ratio in this grain falls in the middle of the range observed in presolar SiC, indicating that this grain is the first recognized example of a presolar oxide mineral. (The smaller measured  $^{26}\text{Mg}^*$  excess of Grain B

gives a higher initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio because there is more 'normal' Mg in Grain B, giving a lower ratio of anomalous to 'normal' Mg.)

Although one corundum grain may seem relatively insignificant compared to the hundreds of SiC and graphite grains that have been measured and the trillions of diamonds that have been recovered, one must remember how heavily the deck is stacked against us. First, rather than chasing a known isotopic anomaly to find the carrier, we must examine elements in a candidate grain until we find one that is isotopically anomalous. There is no requirement that a presolar grain be isotopically anomalous in all elements or in any element. The 'normal' isotopic composition of our solar system is simply the average of the products of many nucleosynthetic sites and that average composition can appear in many places in the galaxy. Thus, we may have measured other presolar grains, but we did not measure an element with a strange enough composition to prove a presolar origin. In future work we will measure the isotopic compositions of other elements in addition to Mg.

Because our criteria for recognizing presolar grains are so restrictive we currently have no information about the relative abundance of presolar oxygen-rich grains and carbon-rich grains. We can place an upper limit on the abundance in Orgueil of the one known type of oxygen-rich presolar grain, corundum. Current data suggest that only a small fraction of the corundum in Orgueil is presolar, but the evidence may be misleading. However, the abundance of presolar corundum cannot exceed the total corundum abundance in Orgueil,  $\leq 0.5$  ppm.

The discovery of a corundum grain that formed with a high initial  $^{26}\text{Al}/^{27}\text{Al}$  ratio brings the number of kinds of presolar grains with high  $^{26}\text{Al}$  content to three; corundum, SiC, and graphite [6].  $^{26}\text{Al}$  was apparently present in the early solar system at an abundance relative to  $^{27}\text{Al}$  of about  $5 \times 10^{-5}$ . An important question is, how was this  $^{26}\text{Al}$  carried into the solar system? One might postulate that the  $^{26}\text{Al}$  was evenly distributed throughout the material that became the solar system, but at a very fine scale, this does not work. The short half-life of  $^{26}\text{Al}$  precludes its presence at the expected abundance in grains that were more than about 10 million years old when the solar system formed. Astronomical mass balance calculations [8] and age estimates from presolar SiC [5]

suggest that most interstellar dust was considerably more than 10 million years old when it entered our solar system. Thus, we need young,  $^{26}\text{Al}$ -rich carrier grains to bring the  $^{26}\text{Al}$  into the solar system. Presolar corundum, SiC, and graphite have the requisite high initial  $^{26}\text{Al}$  contents. By assuming that all of the  $^{26}\text{Al}$  in the grains was alive at the time they entered the solar system we can calculate whether these grains could have been the carriers. As we show in our official abstract, the abundance of these grains are too low for them to have carried the majority of the  $^{26}\text{Al}$ , even under the assumption that all of the  $^{26}\text{Al}$  was alive. With a more reasonable assumption, such as allowing a few million years for transit from the stars at which the grains formed to the solar system, the grains fail by several orders of magnitude to supply the solar system  $^{26}\text{Al}$ . Clearly, the carriers of  $^{26}\text{Al}$  have yet to be found. However, as we have identified and examined no more than a tiny fraction of the possible kinds of presolar dust, the fact that we have not located the carrier of  $^{26}\text{Al}$  does not pose a challenge to our understanding of the early solar system.

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On the isotopic signature of recent solar-wind nitrogen

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One of the most intriguing discoveries yielded by the Apollo samples was evidence pointing towards a significant long-term change in composition of the sun. Such a change, of the size inferred from the lunar sample data, is inconsistent with present theories of solar evolution. Consequently, there is much interest in exploring this phenomenon as closely as possible, to determine exactly what compositional changes have taken place and whether those changes really did take place in the sun, or whether the cause lies elsewhere.

The reason why we can use the moon to analyse the elements in the sun is that the sun emits a stream of ions, known as the solar wind, whose composition, on average, is believed to be the same as that in the surface regions of the sun. When the solar-wind ions hit the surface of the moon, many of them penetrate a short distance into the dust grains lying on the lunar surface. Thus, after a grain has sat on the lunar surface for a while, it has a rim of material that is partly lunar and partly solar in composition. For most chemical elements, the difference between lunar and solar composition is sufficiently small that the solar elements cannot be detected, but for a handful of elements that are missing from the moon, their solar "signature" can be observed in samples of lunar soil brought back by the astronauts. Among those elements is nitrogen, the most common element in the air we breathe, but very rare indeed in the moon.

Like most elements, nitrogen possesses more than one isotope, that is to say, not all nitrogen atoms have the same weight. Although most weigh fourteen units on the atomic mass scale, one atom in about three hundred weighs fifteen units. On earth, variations in the proportion of nitrogen-15 to nitrogen-14 among different samples rarely exceed one percent, but among lunar dust samples, variations of up to forty percent have been found. What is important is that those variations seem to depend on the age of the sample, that is to say, on how long ago it was exposed to the solar wind on the lunar surface.

Our analytical techniques are not sophisticated enough yet to enable us to analyse individual lunar soil grains for nitrogen, much less to zero in on just the nitrogen in the surface of such a grain. Consequently we are forced to analyse samples consisting of many different grains, each of which could have experienced its own individual history. This makes it difficult to identify the nitrogen implanted in grain surfaces, and also to define the age of a sample.

Fortunately, the location of nitrogen atoms within a grain can be inferred from the temperature at which those atoms are released during heating of the sample. The closer to the surface, the lower the release temperature. We can therefore heat a sample in steps and analyse the nitrogen released at each step, to produce a profile of the nitrogen as a function of depth within what can be thought of as an "average" grain, one that is a composite of all the grains in the sample. For a typical lunar dust sample, this picture is complicated by the fact that not all the grains are made of the same material, so that their individual nitrogen release profiles can vary. This problem can be overcome by picking out of a sample a set of grains all made of the same material.

In general, we can determine the age of a sample by measuring the decay of a radionuclide, in much the same way that we can date rocks on Earth. In most cases the resulting age is again a rather complex average of the ages of all the individual grains in the sample, and the significance of that average value is not always clear.

However, for our latest study we have chosen a collection of grains that we believe were all exposed on the lunar surface for the first time by a big meteorite impact 49 million years ago. Although this was a long time ago on the scale of human lifetimes, it was only "yesterday" on the scale of the lunar surface. Consequently, we can use these grains to analyse nitrogen that was recently implanted in the lunar surface. This is important because although we are sure that the proportions of the nitrogen isotopes have changed over time, we do not know what those proportions are in the solar wind today as experiments on spacecraft have not yet been able to make such measurements.

Our latest results gave us three surprises. First, instead of a single value for the proportion of nitrogen-15, our experiments yielded values that decreased progressively as we heated the sample to higher and higher temperatures. This phenomenon had been seen before, but not in such a young sample as ours. The explanation seems to be that nitrogen implanted at different depths within lunar grains has different proportions of nitrogen-15. The depth of the nitrogen may well depend upon how fast it was travelling when it hit the moon. Possibly the speed of the solar wind can vary, or alternatively perhaps the sun emits some ions faster than the solar wind. Whatever the explanation, it will still be a major challenge to explain what is causing the variation in the nitrogen-isotope proportions within individual grains.

The second surprise was that none of our measurements gave a value for the nitrogen-15 proportion as high as we had been expecting. Previous lines of evidence, which were indirect, had led to us to believe that the present solar wind is about eleven percent richer in nitrogen-15 than the Earth's atmosphere. The highest value we found in this work was only seven percent enriched.

Our final surprise was the discovery of a minor nitrogen component never before observed in lunar samples. It is depleted in nitrogen-15 by about six percent relative to air and is only found after oxidising the sample, suggesting that it may be associated with carbonaceous material. Consequently, it may well have nothing to do with the sun or the solar wind, and its origin is still a mystery.

Whether we would be correct to conclude that the recent solar wind is about six percent enriched in nitrogen-15 compared with atmospheric air is not yet clear, and will require further study. More work is also needed to determine whether solar ions of different speed have systematically different isotopic compositions, as suggested by the temperature release of nitrogen.

The nature of the long-term change in the nitrogen isotope proportions is also not yet well defined. Our current best estimate is that about four billion years ago the proportion of nitrogen-15 was about one or two percent enriched relative to air. It apparently then declined about two billion years ago to a depletion of about twenty percent, before rising to an enrichment of six percent, or possibly more, at the present time. What caused these changes remains unknown, but if, as seems likely, the cause lies in the sun, it constitutes a fundamental challenge to our understanding of solar evolution.

**CONSTRAINTS ON THE PUTATIVE COMPANIONS TO PSR1257+12****R. Malhotra, D. Black, A. Eck, and A. Jackson***Lunar and Planetary Institute, Houston, TX 77058, USA.*

The radio pulsar PSR1257+12 was first observed about two years ago by Alex Wolszczan at the Arecibo radio telescope. It has a pulse period of 6.2 milliseconds which makes it one of only a handful of known objects of this type that spin at a dizzying rate of several hundred times per second. Routine followup monitoring of this object has continued since its discovery. Wolszczan and Frail have recently reported that a standard analysis of the time-of-arrival measurements of the radio pulses from PSR1257+12 showed that after accounting for the usual features of millisecond pulsars, there remained a residual in the signal which appeared to be a superposition of two components, one with a period of 98 days and the other with a period of 66 days. They have interpreted this as being due to the presence of two low mass companions in orbit about the pulsar. The amplitude of the individual components in the residuals then gives a measure of the masses of the companions, up to a factor  $1/\sin i$  where  $i$  is the inclination of the orbital plane to the plane of the sky, so that a lower limit of the companion masses is well defined.

The work reported in this paper tests the validity of this interpretation through orbital dynamics. Unlike the case of a single companion, two (or more) planetary companions will perturb each other and their orbital parameters will change with time in a predictable manner. Observation of the signature of precisely such changes in the pulsar radio signals over only a few years will provide unequivocal confirmation of the presence of planets. In addition, the changes, if observed, will allow an accurate determination of the planet masses and hence also the inclination  $i$  of the orbital planes. It should be noted, however, that if the planet masses are no more than 2-3 times the lower limits of  $2.8M_{\oplus}$  and  $3.4M_{\oplus}$ , respectively, the predicted orbital variations are below the current observational errors.

We place an upper limit on the planetary masses by considering the dynamical stability of the three body system. For the inferred orbital radii, we find that the factor  $1/\sin i$  can be no larger than 180 — i.e. the planets can be no more than about twice as massive as Jupiter — if the planetary orbits are to remain stable over any reasonable length of time.

The magnitude and timescales of the orbital changes depend upon the masses of the bodies as well as their relative separation. The observed orbital periods of the two planets are close to a 3:2 ratio. When the periods are close to a ratio of two small integers, the magnitude of the mutual perturbations is highly sensitive to the masses of the planets. We show that for the inferred orbital parameters, there is a “critical” value of the factor  $1/\sin i$  of about 10; above this value, the two planets are *exactly* in the 3:2 resonance, whereas below this value, they are only *near* this resonance. The character of the orbital variations is markedly different in the two situations. Thus, if observations over a few years validate the planet interpretation, the same observations will also easily determine whether or not the planets are in exact resonance.

If confirmed, this system will be the first such known to man. The distribution of planetary masses and their orbital configuration will have important implications for theories of the formation of planets and their orbital evolution, as well for the formation and evolution of pulsars.

## The Thermal Engine of Venus: Implications from the Impact Crater Distribution

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Is Venus a planet running the same thermal engine as Earth or a planet deficient in its cosmochemical share of heat producing elements? Has Venus been dead volcanologically following a great flood of lavas about 500 million years ago, or has the planet been producing magmas more or less continuously? These questions have been raised by the vast amount of imaging radar and altimetric data obtained by the Magellan spacecraft, which has been mapping Venus since September of 1990. Clues about the answers to these questions are provided by the nature and distribution of impact craters on the surface.

Statistical tests show that the distribution of craters on Venus cannot be distinguished from a completely spatially random population. Further, the majority of craters look relatively pristine; only about 5% of the observed craters appear to be embayed or flooded by lavas. The simplest interpretation of these observations is a model in which the impact craters lie on a surface that has been undisturbed by volcanological and tectonic processes since the time the surface was formed. Counting up the number of craters and estimating the rate at which meteoroids strike the surface then gives an age for the venusian surface of 500 million years; in this model the volcanic activity since that time has been essentially nil. This scenario is described as a "production" model, or perhaps more appropriately, a "catastrophic" model. Gerald Schaber of the United States Geological Survey, Steve Saunders of the Jet Propulsion Laboratory, and Robert Strom of the University of Arizona support this view, although they allow that a small, spatially limited amount of surface disruption may have taken place since the catastrophe.

A Venus that has a vast magmatic outpouring covering the entire surface to depths of the order of perhaps one kilometer and then stopping for at least half a billion years is a planet whose mantle is able to build up an enormous

The Thermal Engine of Venus: Phillips R. J.

convective instability that is released as a huge burst. Perhaps Venus has a lower heat source concentration than the Earth, leading to a sluggish style of convection in its interior. Alternatively, the instability may be maintained by a mantle that is significantly stiffer (more viscous) than that of the Earth.

If Venus has not produced lavas in the past half a billion years, then it has done so in the face of the following: (1) Much of the present long-wavelength topography appears, at least in part, to be supported dynamically, implying vigorous upwelling of mantle material and accompanying partial melting. (2) Unless the crust is a great deal stronger than has been estimated, high mountains on Venus must be maintained by presently active tectonic forces; the energy available to drive active tectonism must do so without accompanying volcanism. (3) Coronae (circular tectonic features) are observed in all phases of their life cycle, from the initial uplift phase (novae) to collapse. Coronae are thought to arise from the upwelling of thermal or compositional diapirs, and Venus must continue to produce these features without producing volcanism.

But the simplest interpretation of the crater data may not be the correct one. An alternative model, called "equilibrium resurfacing", is one in which the surface of Venus is in equilibrium between crater production by impacts and crater obliteration by episodic resurfacing events; each event removes craters in a local area of the planet. Geologically, this process is either volcanic covering or tectonic destruction of craters on a regional basis. Although the distribution of these resurfacing events may be random in time, they are statistically well characterized by a steady-state process with a mean resurfacing rate. Advocates of the equilibrium resurfacing model include Roger Phillips of Southern Methodist University, Richard Raubertas of the University of Rochester, and Raymond Arvidson of Washington University in St. Louis.

The atmosphere of Venus has a profound effect on the size-frequency distribution of impact craters. The size-frequency distribution is simply the number of craters as a function of diameter. Theoretical calculations show that for crater diameters larger than about 30 km, the size-frequency distribution is close to the atmosphere-free case. For crater diameters larger than this, the size-frequency distribution can be used to obtain an estimate of the production



# The Thermal Engine of Venus: Phillips R. J.

age of the surface, as noted above, or of the areal resurfacing rate assuming the equilibrium resurfacing model. From the observed distribution, the latter model predicts that Venus is resurfacing at an average rate of about  $1 \text{ km}^2$  per year.

The resurfacing rate derived from the size-frequency distribution is equal to the product of resurfacing patch area,  $a$  (non-dimensionalized by planetary surface area), and the frequency of resurfacing events,  $\omega$ . But only certain combinations of  $a$  and  $\omega$  are possible without violating the constraint that the distribution of craters is completely spatially random (CSR). There are two solution branches that do not violate CSR:  $a < 0.0003$  ( $4^\circ$  diameter) and  $a > 0.1$  ( $74^\circ$  diameter). The former range corresponds to frequent resurfacing events with diameters smaller than the average inter-crater distance, while the latter range is associated with large, infrequent events – from covering 10% of the planet every 50 million years to covering the entire planet once every 500 million years. The end-member  $a = 1.0$  (that is, the “pure” catastrophic limit) can be rejected both statistically and geologically. A significant negative correlation is found between volcanically-embayed and non-embayed craters, indicating that partially flooded craters occur in areas where other craters have been completely removed. Geological associations with high crater density and low crater density areas show that differences in homogeneity of surface albedo and freshness of coronae and craters are consistent with surface age proportional in some manner to crater density. Observations of volcanic unit size tend to favor the small- $a$  solution branch; geologists studying the surface of Venus have concluded that the vast majority of volcanic deposits have areas within the range  $a < 0.0003$ .

The implications for the thermal history of Venus from each of the models (catastrophic vs. equilibrium resurfacing) are obviously significant. Deciding between these two models will require a great deal more work, both statistically and geologically. Continued analysis of the impact crater distribution and its geological associations is a worthy endeavor, one that might tell us the most fundamental aspects of the way in which Venus runs its thermal engine.

**IS THE VENUSIAN LITHOSPHERE SUBDUCTING?**

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Using data collected by the Magellan spacecraft, we are exploring the hypothesis that the cooler and more rigid outer layer of Venus (i.e., the lithosphere) is sinking (subducting) into the interior of Venus. If this process is occurring, it provides a mechanism for cooling the interior of Venus and also for recycling the lighter crustal rocks back into the interior. In addition, since subduction zones drive the plate tectonic motions on the Earth, evidence for lithospheric subduction on Venus raises the possibility of limited plate tectonic-like activity on Venus.

*Earth Tectonics*

The theory of plate tectonics states that the cool and rigid outer layer of the Earth is divided into a small number (about 10) of rigid plates that slide over the hot and weak interior (i.e. asthenosphere). Most of the deformation occurs along the plate boundaries while the interiors of the major plates remain relatively undeformed. There are three types of plate boundaries: plates are created at divergent boundaries (spreading ridge); plates are consumed at convergent boundaries (subduction zone) and plates slide past one another at conservative boundaries (transform fault). Data collected by marine geologists and seismologists over the past 30 years has provided clear evidence for all three types of plate boundaries. A spreading ridge appears as a narrow, linear-rift-zone atop a broad topographic rise, a transform fault appears as long narrow valley and a subduction zone appears as a deep ocean trench with a broad topographic outer rise on the plate being subducted (A-A' in Figure 1). In addition, a subduction zone is an arcuate structure with a topographic ridge on the concave side of the arc and a deep trench on the convex side of the arc (Figure 2). Further evidence for subduction of the oceanic lithosphere comes from the distributions of deep earthquakes which delineate the subducting slab to depths of 700 km beneath the Earth's surface.

*Venus Tectonics*

Preliminary analyses of high resolution Synthetic Aperture Radar (SAR) images and topographic profiles from Magellan have not provided clear evidence for spreading ridges or transform faults on Venus [Solomon et al., 1992]. However there are many arcuate topographic features that resemble Earth subduction zones in both their planform [McKenzie et al., 1992] and their topography [Sandwell and Schubert, 1991; Sandwell and Schubert, 1992].

On Venus, these subduction zone-like features occur on the perimeters of the major coronae. For example, Latona Corona (Figure 3) has about the same radius of curvature and similar topography as the South Sandwich Trench (Figure 2). Moreover, the trench/outer rise topography around Latona Corona is similar in both amplitude and wavelength to the trench and outer rise signature of the South Sandwich Trench (B-B' in Figure 1).

On the Earth, the trench and outer rise are explained as flexure of a thin elastic plate floating on a fluid mantle. The subducted part of the plate is heavier than the surrounding mantle so it imposes a downward force on the end of the plate. Try this simple experiment. Lay a pad of paper on a table so that one half of the pad extends over the edge of the table. Press down on the free end of the pad while holding the other end against the table. An outer rise develops just inside the table edge. Note that the width of the outer bulge depends on the thickness of the pad.

We have applied this type of flexure model to the trench and outer rise topography of 4 major coronae and 6 Earth trenches. For each trench, the best fitting model provides an estimate of the effective elastic thickness of the lithosphere (e.g., the thickness of the pad) as well as the bending

moment needed to support the outer rise (i.e. the amount of downward force applied to the end of the pad).

The elastic thicknesses determined by modeling numerous profiles at 4 coronae (Eithinoha, Heng-O, Artemis, and Latona) are 15, 40, 35, and 37 km, respectively. Similar elastic thicknesses are found at the 6 Earth trenches as shown in the table below. At Artemis and Latona where the lithospheres appear to be yielding, the maximum bending moments are similar to those found at the Kuril and Aleutian Trenches. These results suggest that the thickness and strength of the Venusian lithosphere is similar to the thickness and strength of terrestrial lithosphere despite the higher surface temperature of Venus.

#### LITHOSPHERIC THICKNESS

	Elastic Thickness (km)	Bending Moment ( $10^{16}$ N)	
Freyja Montes	18	0.6	VENUS
Eithinoha Corona	15	0.9	
Heng-O Corona	4	1.0	
Latona Corona	35	6.1	
Artemis Corona	37	25.4	
Middle America Trench	12	0.6	EARTH
Chile Trench	20	3.2	
Aleutian Trench	30	7.8	
Peru Trench	40	9.4	
Izu-Bonin Trench	40	18.4	
Kuril Trench	45	22.5	

#### *Where are the Spreading Ridges?*

If one believes that the trenches around major coronae are sites of lithospheric subduction, then one must ask, where is the lithosphere being created? On the Earth lithosphere is created along two basic types of spreading ridges. Most of the lithosphere is created along spreading ridges that are far from the subduction zones. In this conveyor-belt type model, plates are created at the spreading ridges and they slide across the surface of the Earth until they reach a subduction zone where they are consumed. However, a much smaller fraction of the lithosphere is created along spreading ridges that are located behind the trench axis on the overriding plate (Figure 4). In this type of "back-arc" spreading, the plate sinks vertically so that the trench axis migrates toward the convex side of the arc. Back-arc spreading occurs in order to fill in the void left behind by the sinking plate. In the case of the Sandwich Trench (Figure 2), the trench has migrated eastward for about 2000 km leaving the young Scotia plate behind.

We speculate that this back-arc type spreading is occurring in the interiors of the major coronae (Figure 4). However, since trenches enclose several of the major coronae by more than  $180^\circ$ , the back-arc spreading must occur in all directions. The other possibility is that spreading occurs along linear rift zones, like on the Earth, but these rift zones constantly reorient themselves to keep

the interior of the corona relatively round. An examination of Magellan SAR images reveals widespread extension inside of coronae consistent with pulling apart and infilling although we do not see evidence for organized spreading ridges like on the Earth.

The remaining question is whether the lithosphere outside of the coronae has been subducted over great distances or if the trench is formed by a limited amount of overthrusting. The difference between these two models has major implications for the thermal and chemical evolution of the planet. We are attempting to distinguish between the subducting and overthrusting models by first determining the upward force (bending moment) needed to support the outer rise topography and comparing this with the downward force that can be supplied by the topography of the overriding plate. If the overriding plate is not heavy enough to supply the required force then we will speculate that the missing force is supplied by subducted lithosphere. Of course to prove that the Venusian lithosphere is subducting, one needs more direct evidence such as on Earth where the distribution of deep earthquakes delineate the subducting slab to depths of 700 km.

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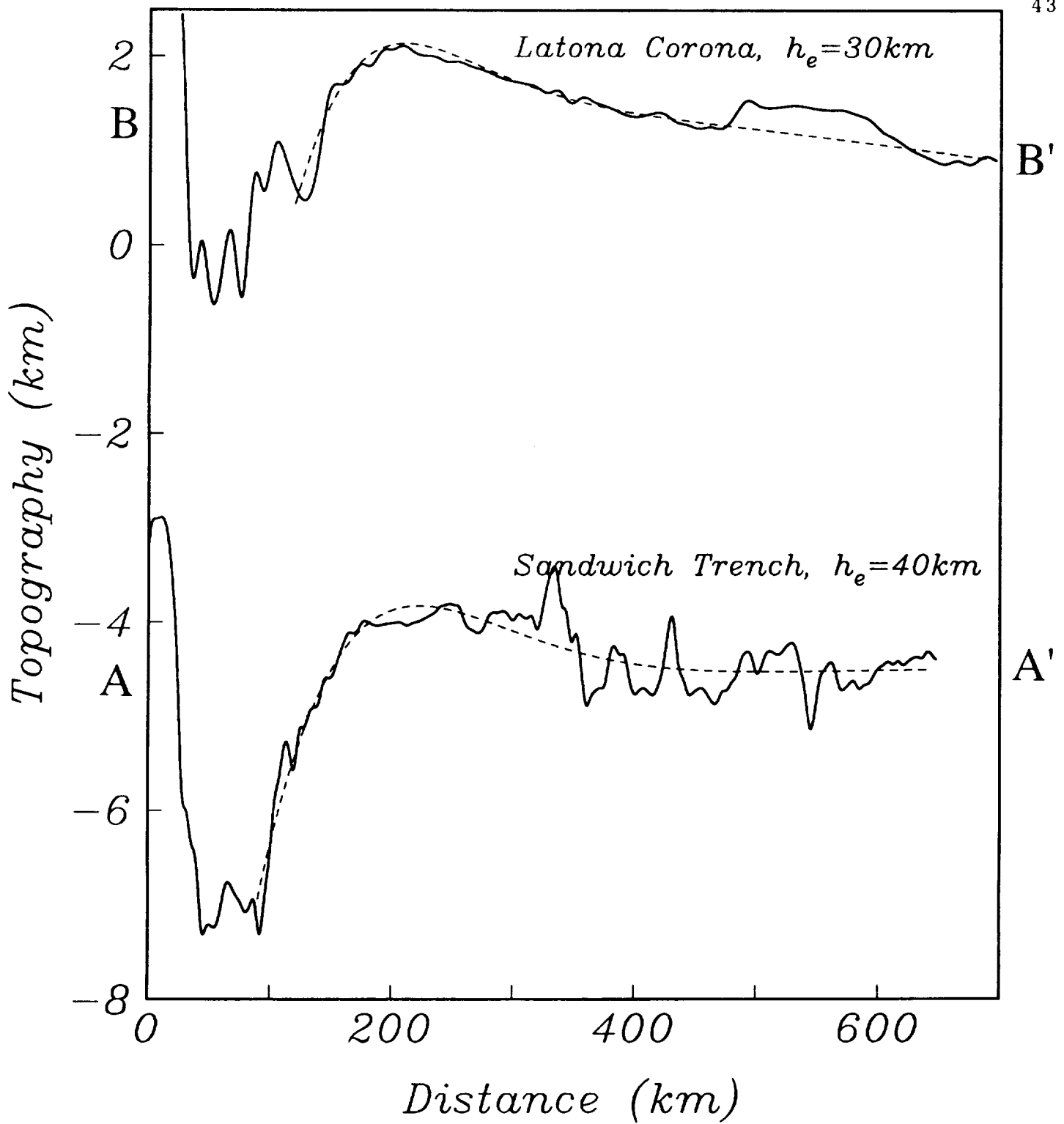


Figure 1. Topographic profile across the South Sandwich Trench (A-A' in Figure 2) and the southern trench at Latona Corona (B-B' in Figure 3).

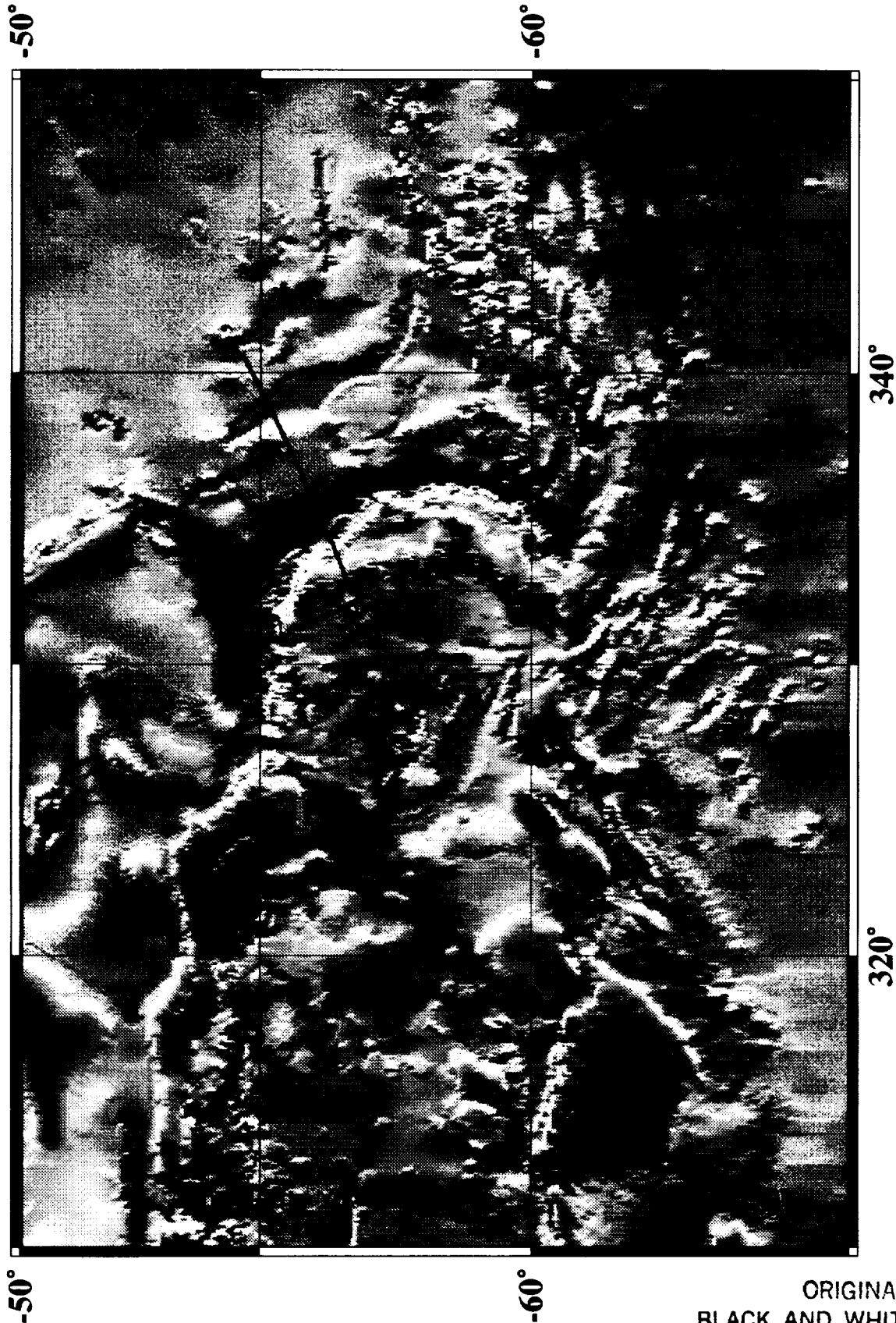
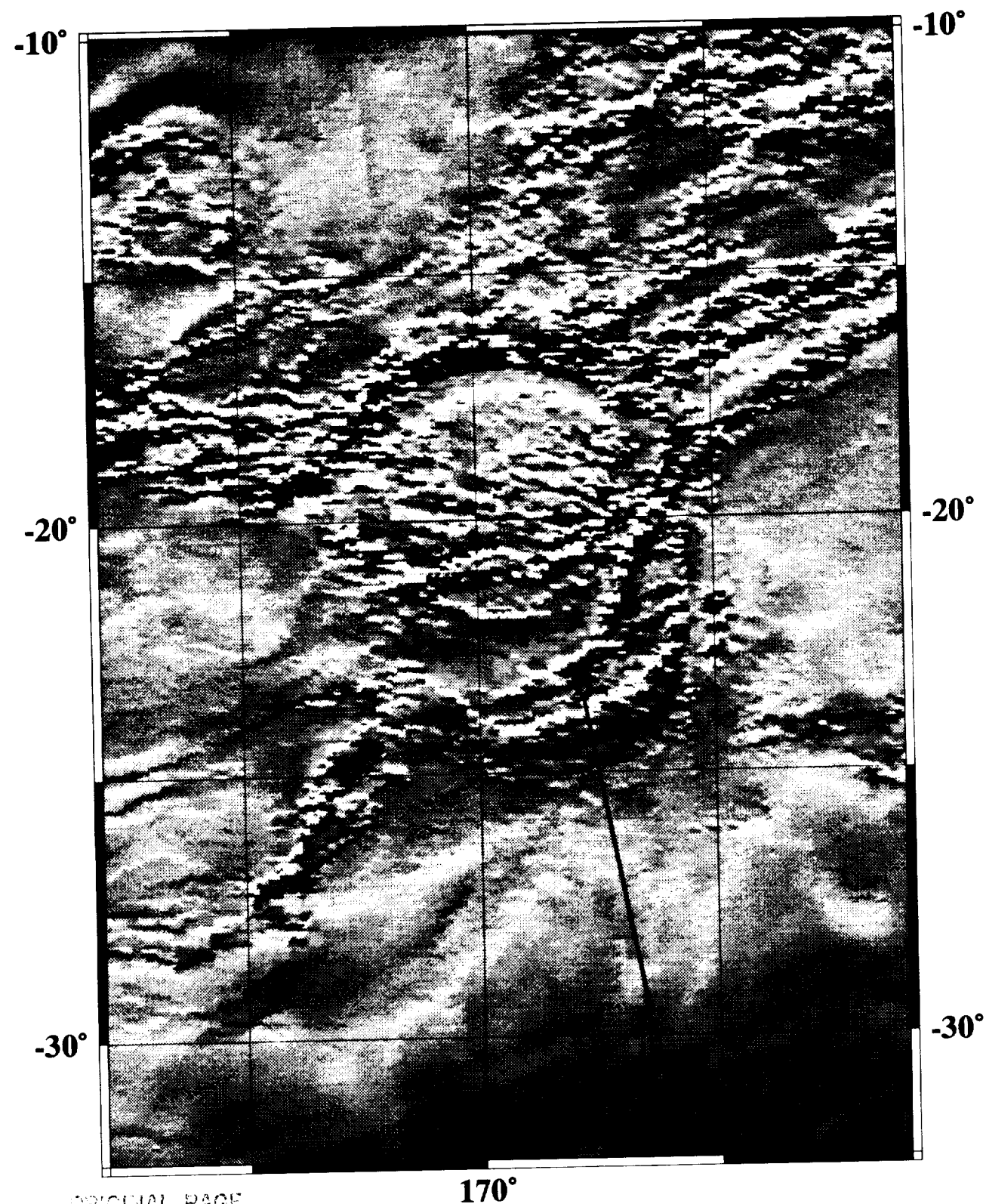


Figure 2. Topography of South Sandwich Trench (South Atlantic, Earth) illuminated from the east. The trench has a 350 km radius of curvature. Profile A-A' is shown in Figure 1.



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BLACK AND WHITE PHOTOGRAPH

Figure 3. Topography of Latona Corona (Eastern Aphrodite, Venus) illuminated from the north. The horizontal scale and vertical color scale is identical to those in Figure 1 so features can be compared. Latona Corona has a 360 km radius of curvature, similar to the South Sandwich Trench. Profile B-B' is shown in Figure 1 for comparison with the South Sandwich Trench profile.

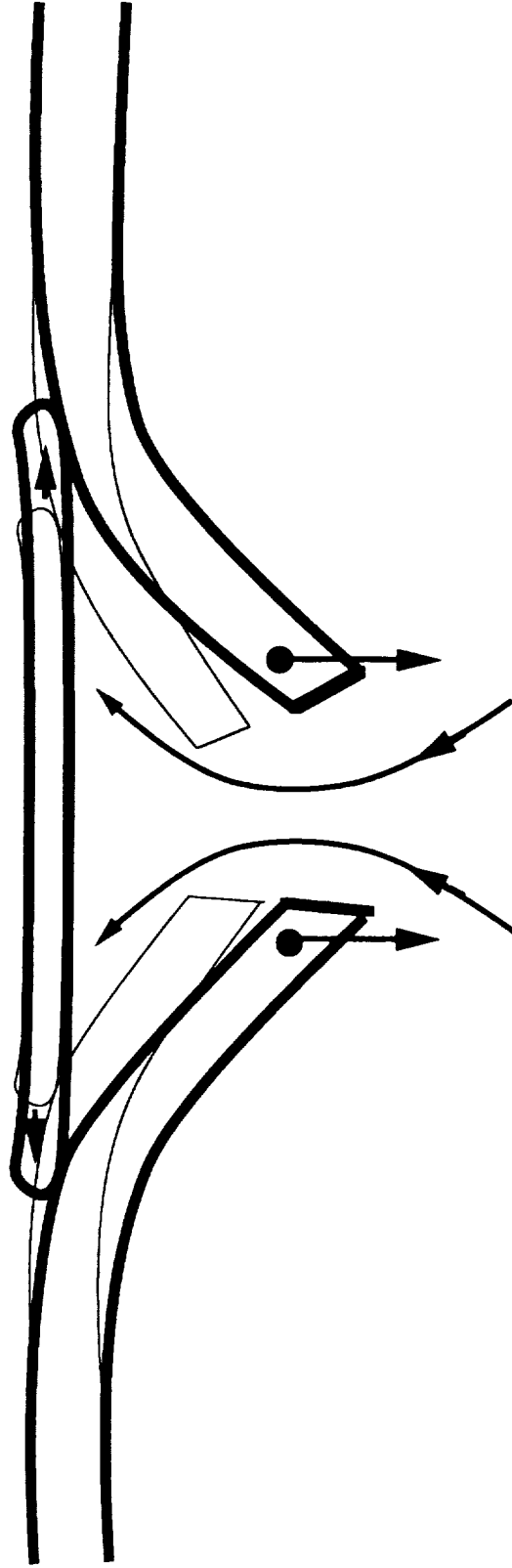


Figure 4. Schematic diagram of lithospheric subduction where slab sinks vertically and interior plate expands to fill the void.



## SCIENCE QUESTIONS FOR THE MAGELLAN CONTINUING MISSION, R.S. Saunders and E. R. Stofan, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109.

Magellan has completed two mapping cycles around the planet Venus, returning high resolution synthetic aperture radar images and altimetry data of over 95% of the planet's surface. Venus is dominated by low-lying volcanic plains with an impact crater population indicating an average surface age of about 500 my [1]. Highland regions either tend to be characterized by volcanic shield complexes and rifting (i.e., Beta Regio, Eistla Regio) or by complex ridged terrain (i.e., Alpha Regio, Ovda Regio).

Successful as the primary mission of Magellan has been, significant science questions remain to be addressed with imaging and gravity data that will be collected over the next several years. The origin of highland regions on Venus remains a topic of controversy. Models for highland origin include both upwelling and downwelling in the Venus mantle [2,3]. Complex ridged terrain (tesserae) may also be remnants of older, lower density crustal material that has experienced many episodes of resurfacing and tectonic disruption. While no terrestrial-style system of plate tectonics has been identified on Venus, arc-like troughs in eastern Aphrodite Terra show morphologic and topographic similarities to subduction zones on Earth [4]. Hotspots may be a major mechanism of heat transfer, producing features ranging from volcanic rises such as Bell Regio to large circular features called coronae. Hotspots are surface volcanic features, such as Hawaii, formed over hot plumes rising from deep in the interior of a planet.

Gravity data provides quantitative information about what is going on in the interior of a planet. Models of the origin of various highland regions on Venus differ greatly, and can be directly tested with gravity data. The extended mission plan is to collect a full 360 deg. of gravity data using a lowered periapsis (180 km vs. 300 km) for improved spatial resolution. Gravity feature resolution is approximately equal to the spacecraft altitude. The quality of the Magellan Doppler gravity data will be significantly improved over the Pioneer Venus data. The noise level of the Magellan doppler data will be at least a factor of five lower than the PV data as Magellan has an X-band (3 cm wavelength) transmitter. This will provide a better relative accuracy within a profile; specifically, because as resolution improves, error decreases and smaller scale features can be modeled. The largest improvement in gravity data coverage will be obtained in the southern hemisphere with factors of 3 or more increase in signal amplitude over previous PV data. An even better gravity experiment, nearly optimal, could be carried out with a low circular orbit at approximately 200 - 350 km altitude. This orbit would provide uniform resolution over the entire planet. Many of the smaller scale features on Ishtar Terra could be resolved and compared in detail directly with results obtained for Beta, Atla, Aphrodite, etc. One could accomplish this geometry with aerobraking (i.e., letting the Venusian atmospheric drag circularize the orbit). The time required to bring this about would be about three months or less and could be accomplished in the fifth cycle, beginning about May 1993 after complete gravity coverage is obtained with the present orbit (after lowering periapsis to 180 km).

**MAGELLAN EXTENDED MISSION SCIENCE: Saunders, R.S. and Stofan E. R.**

Major science questions also remain on the detailed topography of surface features. Data obtained using different incidence angles of the radar from those used in the first mapping cycle will permit stereo viewing of the surface and production of image-scale resolution digital elevation models of the Venus surface. Stereo images will permit better geologic mapping of the surface, as well as improved topographic information on volcanic and tectonic features.

Is Venus a dynamic planet like Earth? Remapping of specially targeted areas over the next several years may provide evidence, such as changed patterns of lava flows, landslides, and new or altered wind features, that Venus is still an active planet. Several volcanic regions have been targeted as possible sites of relatively recent volcanism. One such target is Maat Mons, the highest volcano on Venus, whose surface has not yet been altered to form the highly reflective material characteristic of other high peaks on Venus [5]. In addition to volcanism, areas with high concentrations of wind streaks will be re-imaged, to try and detect variability in Venus wind patterns.

This work was done at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.

**REFERENCES:** All the references cited, along with other relevant papers, are to be included in a special Magellan issue of JGR Planets to be published in mid 1992. [1] Phillips et al., 1992 [2] Bindschadler et al., 1992 [3] Gimm et al., 1992 [4] McKenzie et al., 1992 [5] Wood et al., 1992.

GASPRA'S SHAPE AND SURFACE FEATURES: COMPARISON TO SMALL SATELLITES, P. C. Thomas, M. E. Davies, RAND, D. Simonelli, J. Veverka, Cornell Univ., M. J. S. Belton, NOAO.

The several thousand asteroids constitute the second largest population of substantial solid objects in the solar system (there are probably more comets), and have been studied from the earth for nearly two centuries. Asteroids are important members of the solar system for several reasons, among them: 1) They contain materials that reflect the processes going on early in the time of planet formation, 2) their impacts have been the major external influences on the surfaces of some terrestrial planets, and 3) their impacts on earth have probably had major effects on biologic evolution. Despite their importance, the first picture of an asteroid was not obtained until the Galileo spacecraft flew by Gaspra on October 29, 1991. In this image Gaspra is about 75 by 95 picture elements across; image resolution of small satellites are better only for the martian moons Phobos and Deimos, and Neptune's Proteus, though several others have been imaged nearly as well.

The initial exploration of any solar system body involves comparison to known objects and a search for predicted features. The objects most likely to be similar to small asteroids are small satellites and comet nuclei. Bodies smaller than a few hundred km in mean radius are unlikely to have generated enough internal heat to produce volcanism or mountain building, and they cannot hold an atmosphere. Thus asteroids should have some similarities to small

satellites in being shaped largely by the external forces of collisions and cratering. The comparisons could be complicated by different compositions, as well as by the likelihood that asteroids lose more material from impacts than do small satellites. The latter tend to reaccumulate material knocked off by impacts because that debris merely goes into orbit about the planet, close to the satellite, and will quickly be swept up again by the satellite. Material ejected from asteroids is effectively permanently lost.

The Galileo view of Gaspra shows a highly irregular shape. It is apparently only one object, contrary to some early suggestions that it might be two closely orbiting bodies. Gaspra's shape can be described as smooth, gently curving surfaces intersecting along ridges. The outline (limb) has two concavities that are over 8km across, greater than the average radius! Such concavities have been seen on small satellites, such as the martian moons Phobos and Deimos, but as a fraction of the object's radius, Gaspra's limb is more irregular than any small satellite. The concavities are thought not to be simple impact craters but rather irregularities left by the global fragmentation of a larger precursor body. Collisions with other asteroids should disrupt a Gaspra- sized, rocky object in a time short compared to the age of the solar system. The number of craters visible on the surface that have formed since this catastrophic event suggest an age of only a few hundred million years, 1/10th or less the age of the solar system. If this object has a large metal fraction, however, it might be strong enough to survive much longer, and the calculated surface

age could be much older.

One common prediction about small asteroids has been that they would have very little or no loose debris (regolith) on the surface because their weak gravity (escape velocity on Gaspra is probably only a few meters/second) would not hold impact ejecta. However, the smooth appearance and the exposure of different colored materials by some craters suggests that there is at least some loose surface material. The different colors seem to occur on ridges; this correlation suggests that debris is preferentially removed from the higher areas. We know that even very weak surface gravity can move regolith downslope (seen on the martian satellites), but what is less clear is how ejecta from craters are kept on the asteroid in the first place. The later, higher resolution image may give information on the depth of any loose material Gaspra. If it is deep, ideas on mechanisms for its formation and distribution may have to be substantially updated.

The possible amount of regolith is just part of the overall picture of the physical configuration of this asteroid: is it one solid, very strong object, either rocky or metal? Is it a loose agglomeration of rocky and/or metallic bodies? Is it all very fine, loose material? The latter is unlikely because impacts would quickly disperse the pieces. The question of constitution and strength of the asteroids relates to how effective they are when they hit something, either other asteroids or the terrestrial planets. Accurately connecting the geologic record of cratering rates on the earth with the number and sizes of asteroids and comet

nuclei is needed to evaluate the past and possible future influence of impacts on the terrestrial planets. The amounts of regolith and strength of the interiors of asteroids also bears on the eventual feasibility of resource extraction from asteroids.

The size distribution of craters on Gaspra is also different from that seen on small satellites: there are very few intermediate and large (over 1 km) craters. This difference might arise from the last catastrophic impact being geologically recent or from more efficient hiding of small craters on satellites by recapture of more impact ejecta than on asteroids.

The overall first impression of Gaspra is that it is something of a cousin to small satellites: recognizable, but with substantial differences. The higher resolution data to be received later should tell more about how similar small satellites and asteroids can be.

## DISCOVERY OF TWO PLANETS AROUND A MILLISECOND PULSAR

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By timing the arrival of radio signals from a rapidly spinning pulsar at the Arecibo Observatory's radio/radar telescope, the most convincing evidence so far for a planetary system outside our own has been found: two or possibly three planets that orbit the neutron star called PSR1257+12. This finding indicates that planet formation may be a more common process than previously anticipated and that the formation of disks of gas and dust that are sufficiently massive to condense into Earth-sized planets orbiting their central bodies can take place under surprisingly diverse conditions.

NAIC and the Arecibo Observatory, whose 305-meter-diameter dish is the world's largest and most sensitive single telescope for collecting radio signals from space, are operated for the National Science Foundation by Cornell University. A detailed report on the discovery of planet-sized bodies orbiting PSR1257+12 has been published in *Nature* on Jan. 9, 1992.

The pulsar under study is a rapidly spinning neutron star; it is made of matter that is squeezed to extreme densities as the result of the collapse of a parent star during a supernova explosion. It is called a pulsar because the continuous beam of radio energy rotating together with the star appears, to a stationary observer, to be a pulse as it sweeps through space.

PSR1257+12 was discovered in February 1990 with the Arecibo telescope during a search designed to detect short period pulsars; the existence of PSR1257+12 was unraveled in the process of a massive data analysis on the Cornell National Supercomputer Facility. A long series of observations made between July 1990 and November 1991 revealed the following information about the pulsar and its planetary system.

- PSR1257+12 is an old pulsar, with more than 1 billion years having elapsed since it and a binary companion were formed as ordinary stars, out of a gravitationally contracting interstellar cloud. Some ten million years after the binary formation, the more massive of the pair underwent a supernova explosion and its collapsed core became a neutron star. Further evolution of the remaining stellar companion caused accretion of some of its expanding envelope onto the neutron star. This process helped to spin the pulsar up to a 6.2 millisecond rotation period observed today. The companion itself had been probably vaporized by the pulsar's high energy radiation and supplied material for a formation of planets that are now seen orbiting PSR1257+12.

- PSR1257+12 is a millisecond pulsar sweeping Earth with its radio beam once every 6.2 milliseconds, or 162 times a second. An extraordinary stability of its rotation

means that for many practical purposes it can be used as an ultraprecise clock. Astrophysically, PSR1257+12 is "immortal" in the sense that it is expected to be observable at least as long as the present age of the universe (about ten billion years). So, probably, will its planets. The pulsar and its planetary system are far from Earth – 1,300 light years or 7,500,000,000,000,000 miles – and too faint to be easily observed by optical or infrared telescopes. PSR1257+12, like other neutron stars, has a mass about 1.4 times that of the sun, but it is only 0.000014 its size, with a radius of about 10 kilometers.

- Two planets are orbiting PSR1257+12 about 33.5 million and 43.7 million miles (or 0.36 and 0.47 Astronomical Units) away from the pulsar, about the same distance that Mercury is from the sun. Both are moving in nearly circular orbits, taking 66.6 and 98.2 Earth days to complete each revolution. A detailed analysis of the observations made to date suggests the existence of one more planet circling the pulsar about 1.1 Astronomical Units away and with an orbital period close to one Earth year, a possibility that may be confirmed by additional measurements. The newly discovered planets' masses are greater than that of Earth, at about 3.4 and 2.8 Earth masses. In principle, they are massive enough to retain atmospheres but it is likely that any atmosphere would be blown away by the pulsar wind composed of relativistic particles and hard radiation. The pulsar's planets may have densities similar to those of our inner solar system planets, because they probably condensed from the dust particles in the disk made of the evolved matter of PSR1257+12's former binary companion. In density, composition and size, these planets may be not unlike Earth or Venus.

- PSR1257+12 is wobbling in space. Responding to the gravitational pull of its planets, the pulsar exhibits a reflex motion and wanders around the center of mass of the pulsar – planets system. This makes it periodically approach the Earth and recede from it, covering a distance of about 900 kilometers either way. One planet would cause a perfectly circular wobble; because of the effects of two or more planets, the wobbling motion is a more complicated, quasi-periodic oscillation. It is that wobble that affected the precisely measured arrival times of pulsar signals at the Arecibo telescope and allowed the detection of the planets. When the pulsar is farthest from Earth, the radio pulses take about three milliseconds (three one-thousandths of a second) longer to reach Earth; at the nearest point in the wobble, signals arrive three milliseconds sooner.

Faint signals from the distant pulsar collected by the huge dish of the Arecibo telescope were amplified in a receiving system and then digitized and recorded on a computer tape along with timing information from an atomic clock. In almost one and one-half years of observations, more than 4,000 accurate measurements of pulse arrival times were made. A quasi-periodic wobbling pattern seen in these data is most plausibly accounted for by a model involving the pulsar's reflex motion caused by the presence of two orbiting planets. This model is accurate enough to repeatedly and reliably predict pulse arrival times at any given epoch. All the most plausible alternative explanations



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have been rigorously examined and ruled out. Among them were neutron star seismology (or star quakes) that may cause quasi-periodic timing variations and glitches in much younger pulsars, as well as a wobble of the pulsar spin axis, interstellar propagation phenomena and instrumental effects. Contrary to a one-planet case, an "absolute" proof can be obtained for more planets by modeling their mutual gravitational interaction and comparing this model with the timing data. Conclusive results of this comparison will be available within 2-3 years.

Because of its exceptional accuracy, the pulse-timing technique, especially when applied to millisecond pulsars, can detect planetary masses even smaller than that of Earth's moon. So far, no positive identification of an extra-solar planetary system has been made with optical or infrared search methods, which are much less sensitive. If "terrestrial-type" planetary companions to very old neutron stars are indeed not entirely uncommon, pulse-timing will become the most useful method to identify and study planetary systems other than our own. Further detections of millisecond pulsars in the solar neighborhood will help to verify this truly exciting possibility. Several such searches have recently begun at Arecibo and elsewhere. The chance of a non-negligible frequency of occurrence of planets around neutron stars, if confirmed, will undoubtedly have far-reaching consequences for our understanding of the formation and evolution of planetary systems and for future strategies of searches for planets outside the solar system.

**This text is based on the Jan. 9, 1992 Cornell University press release on the discovery of planets around PSR1257+12.**





